# CASTING OF ALUMINIUM STRIPS USING SINGLE ROLL CONTINUOUS STRIP CASTER

*by*

**PANKAJ NRIPENDRACHANDRA BID**



**DEPARTMENT OF METALLURGICAL ENGINEERING**

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

**APRIL, 1993**

# CASTING OF ALUMINIUM STRIPS USING SINGLE ROLL CONTINUOUS STRIP CASTER

*A Thesis Submitted*
*in Partial Fulfilment of the Requirements*
*for the Degree of*
**MASTER OF TECHNOLOGY**

*by*

PANKAJ NRIPENDRACHANDRA BID

*to the*

DEPARTMENT OF METALLURGICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
April , 1993

2/4

P.M.

# CERTIFICATE

This is to certify that the work "Casting of Aluminium Strip Using Single Roll Continuous Strip Caster" has been carried out by Mr. Pankaj Nripendrachandra Bid under my supervision and it has not been submitted elsewhere for a degree.

S. P. Mehrotra
2/4/93

Dr. S. P. Mehrotra
Professor
Department of Metallurgical Engineering
Indian Institute of Technology
Kanpur

# ABSTRACT

The Single Roll Strip Casting Process is a near-net-shape-casting process of producing the flat products. In this process, molten metal from a tundish/reservoir is allowed to flow on to the surface of a rotating hollow caster drum which is cooled from inside by water sprays. As soon as the bare surface of the drum comes in contact with the molten metal, thin skin of metal is formed on its surface due to the instantaneous solidification of the metal. This skin of metal continuously grows as long as it remains in contact with the molten metal in the molten metal pool.

The present investigation is a part of an on going major project in our laboratory on the design and development of a Single Roll Strip Caster. This part of the project primarily deals with the design and fabrication of a laboratory scale caster, and then generation of experimental data on aluminium strip production under various operating conditions using this caster. Data, thus generated, are being used for validation of the mathematical model, developed in the first of this project.

The Single Roll Strip Caster has been successfully designed and fabricated. A microprocessor based control system has been incorporated to control the speed of the stepper motor which is used to rotate the caster drum. A gear assembly has been designed and fabricated to enlarge the range of the rotational speed of the drum beyond the range that is obtained by using the stepper motor alone. The cooling of the drum is done by water sprays through specially designed nozzles. A provision is made to continuously monitor the temperature of the caster drum wall at, atleast two

locations during the casting process. The temperatures are measured through separate thermocouples - the output of the thermocouples is directly fed to a PC based data acquisition system.

More than sixty experiments have been carried out to produce aluminium strips using this caster under various operating conditions to study the effect of these variables on the strip thickness. The variables examined include; (i) rotational speed of the caster drum, (ii) liquid metal head in the tundish, (iii) superheat of the melt, (iv) standoff distance, (v) nozzle gap, and (vi) cooling conditions prevailing at the inner surface of the drum. Rotational speed of the drum is the most critical parameter. It is observed that the strip thickness decreases with increasing rotational speed and melt superheat, but increases with increasing standoff distance and metal head in the tundish. Nozzle gap and the cooling conditions prevailing at the inner surface have only very marginal effect on the strip thickness.

# ACKNOWLEDGEMENT

I am extremely grateful to my guide Professor S. P. Mehrotra for suggesting the interesting problem, inspiring guidance, valuable discussions and constant encouragement through out the course of this study. He has been very creative to me through out this investigation without which the work in the present form may not have been possible.

I would like to express my sincere thanks to Mr. M.R.R.I. Shamsi, Mr. R. K. Singh, Mr. A. Dutta and Mr. D. N. Patel for helping me during the experimental work as well as valuable suggestions rendered by them in the present study. I am thankful to Mr. K. S. Tripathi and Mr. D. P. Tripathi for their valuable help and active cooperation during the entire period of this work.

I am also thankful to Mr. D. K. Biswas of Engineering Metallurgical Laboratory for providing me some urgently needed chemicals for this work.

I would like to thank Mr. V. P. Gupta for tracing the figures and Mr. Yash Pal for taking enormous pains in typing this thesis and their sincere cooperation.

I express my sincere thanks to Mr. Kamlesh K. Singh and Mr. K. S. Rao for their help during my thesis work and to all my friends with whom I have had many days of pleasant association in the campus.

Finally I would like to offer my sincere thanks to my family members and relatives for their inspiration and encouragement in this study.

Pankaj Bid

April 1993 Pankaj N. Bid
Kanpur

Contents

## List of Figures

## List of Tables

# CHAPTER 1

# INTRODUCTION

The conventional method of producing metallic strips/sheets generally involves casting of large slabs or ingots which are then hot and cold rolled to get the desired product thickness. In the conventional method beside rolling several other unit operations such as soaking, slab grinding, intermediate annealing etc are also required. These operations are quite expensive and require a large amount of energy. As a result, the cost of production is high and productivity is low. An alternative to this conventional route of strips/sheets production is the near-net-shape-casting in which many of the above mentioned unit operations are eliminated. The objective in these processes is to directly transform the molten metal into strips/sheets, the dimensions of which are quite close to the desired dimensions. Figure 1.1 enumerates the unit operations involved in producing flat products using conventional continuous casting and near-net-shape-castings routes.[1,2] The latter results in a lot of energy and time savings, and high productivity with minimum percentage of returns. Table 1.1 presents energy consumption in producing plain carbon steel strips/sheets by three different routes: (i) Ingot Casting[3] Route (ii) Conventional Continuous Casting Route (iii) Direct Strip Casting or Near-Net-Shape-Casting.

For direct strip casting processes the energy required include the energy used for ladle heating, holding, tundish

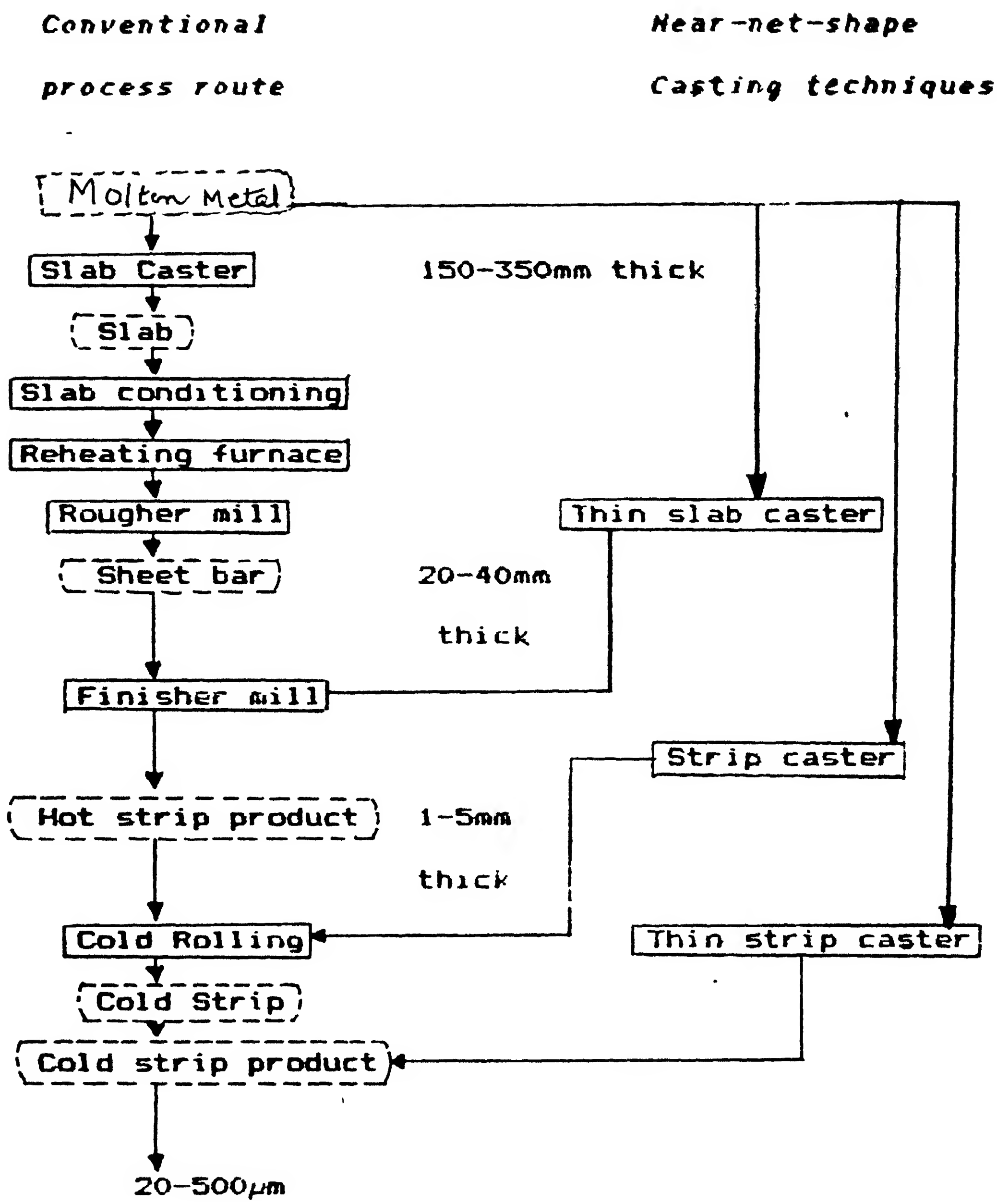



Fig. 1.1 Process routes for producing flat rolled products[1]

preheating casting and post casting operations like annealing, rolling etc. Table 1.1 indicates that about 68% energy saving is possible by near-net-shape-casting in place of ingot route. Comparison to the conventional continuous casting process indicate that a saving of 61% energy from the use of the latter is possible.

The near-net-shape-casting not only results in large energy savings but may also result in production of superior quality.

The direct casting of strips or sheets from molten nonferous metal has already been in use on commercial scale for production of aluminium, lead and zinc since 60's.

The continuous near-net-shape casting processes can be classified into four categories, depending on the thickness of the final product.[2]

1. The thick slab caster producing 20-100 mm thick slab which could be directly fed into the finisher mill for hot rolling.
2. The thin slab caster producing 10-20 mm thick slab which need some limited hot rolling due to the metallurgical reasons.
3. The strip casters producing strip less than 10 mm thickness which may directly go to the cold rolling plant.
4. The thin strip caster which would produce directly a final product equivalent either to the as rolled sheet or to the cold rolled sheet. The thickness of the product here may be a fraction of a mm.

**Table 1.1 : Comparison of the energy required to make carbon steel strip/sheet by the three processes[3]**

| Process | kWh/ton production | kWh/ton shipped | % material loss |
|---|---|---|---|
| Ingot casting | 1760 | 2394 | 27 |
| Continuous casting (conventional) | 1442 | 1933 | 25 |
| Direct strip casting | 721 | 750 | 4 |

As will be discussed in the following chapter on Literature Review, several processes which fall in the general category of near-net-shape-casting processes have shown potential for commercial exploitation.[2,4-6] One of these processes which has been the subject of the present investigation is the Single Roll Continuous Strip/Sheet Caster. A brief description of this caster is given below:

## 1.1 SINGLE ROLL CONTINUOUS STRIP/SHEET CASTER[7,8]

Schematic representation of the process is shown in Figure 1.2. The liquid metal at a particular temperature is held in the tundish in which its level is always kept constant. The tundish has a rectangular nozzle opening at the bottom of the side wall facing the caster drum through which the molten metal continuously flows into the liquid metal pool contained in the annular space between the rotating water cooled drum and the tundish wall. The rotating drum drags along with it a part of the metal from liquid metal pool which on solidification forms a thin skin of solidified metal strip. This skin continues to grow as long as it is in contact with the molten metal in the pool. A Knife edge located on the other side of the caster drum peels off the solidified strip from the drum after it has grown to its full thickness. Heat is continuously extracted from the solidified strip through the caster drum by water spray nozzles located inside the hollow drum. For a given liquid metal head in the tundish strips of different thicknesses can be produced by varying the speed of

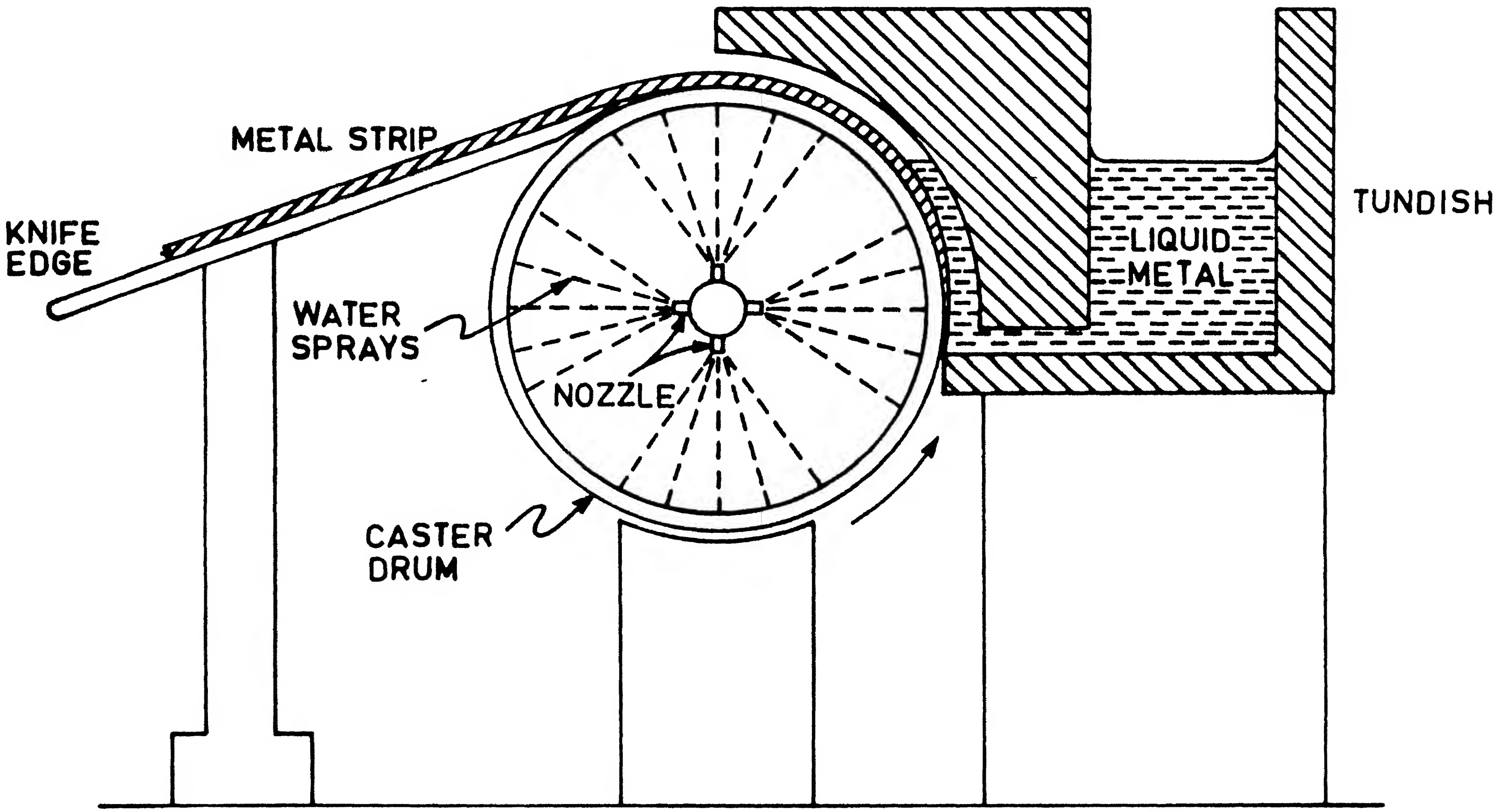



Fig. 1.2 Schematic sketch of the Single Roll (drum) Horizontal Strip Caster

rotation of the caster drum.

At the point of first contact between the caster drum and the liquid steel, say at angular position $\beta_1$, there is instantaneous solidification, and skin of initial thickness is formed. This skin continuously grows during its sojourn through the liquid pool and attains its final desired thickness at the exist end of the pool at angular position $\beta_2$. The solidifying strip remains in contact with the liquid pool over the angular position which in turn, is directly related to the metal head in the tundish.

The entire process can be divided into four distinct zones (i) liquid steel tundish including the nozzle channel, (ii) liquid steel pool, (iii) solidifying steel strip, and (iv) water cooled caster drum.

The liquid pool is bounded by tundish walls and solidifying steel strips on sides and protruding tundish wall at the bottom. The top free surface is open to atmosphere. The molten steel from the pool is being continuously removed in the form of the solidifying strip and this loss of metal in the pool is being replenished continuously by flow of metal from tundish. At steady state the two rates are equal such that the liquid steel level in the pool always remains constant. One surface of the solidifying strip is attached on to the caster drum whereas the other surface is interfaced with molten steel in the liquid pool. It is assumed that the strip is firmly adhered to the caster drum and that there is no slip between the two. The strip is assumed to be moving at

the same speed as the caster drum and the residence time of the solidifying strip in the liquid steel pool is directly related to the speed of rotation of the drum which, in turn, determines the final thickness attained by the strip as well as the production rate.

## 1.2 OBJECTIVE OF THE PRESENT INVESTIGATION

The present investigation is a part of a major project which is currently underway in our laboratory. The project involves developing a comprehensive mathematical model ultimately leading to design criteria for such a caster, validation of mathematical model using experimental data generated on a laboratory scale single roll strip caster, and finally to examine the feasibility of using such a process for producing steel and non ferrous metal strips/sheets. The present study partially deals with the latter two objectives. In the first part of this investigation the fabrication of the single roll caster initiated by Mehrotra and coworkers,[19-24] was completed. The caster was first tested using wax and low melting point metals like tin and tin-lead alloys. The second part, which represents the bulk of this study, involved: (i) production of aluminium sheets/strips under various operating conditions, and (ii) the study of the effects of various operating parameters on the final strip thickness and the quality of sheets in terms of the surface finish as well as the number of cracks formed. The sheets produced in these experiments are being separately tested by another group for their mechanical properties

and microstructure to establish that the product of single roll caster is as good or even better than the product of conventional methods. The experimental data generated in this study is being used by Mehrotra and coworkers to validate the mathematical model developed by them.

# CHAPTER 2

# LITERATURE REVIEW

In this chapter a brief description of various near-net-shape casting processes, which have been developed so far and/or have shown potential for commercial exploitation is presented. The one which have been employed for the casting of non-ferrous metal in general, and aluminium in particular have been emphasised.

## 2.1 DESCRIPTION OF VARIOUS NEAR-NET-SHAPE-CASTERS

For any near-net-shape caster to be successful on the industrial scale certain minimum requirements must be fulfilled[2].

1. Their productivity must atleast match with that of one strand of a conventional caster producing the same width in order to a avoid excessive multiplication of casting strands. This means that the casting speed has to be increased in inverse proportion to the ratio of thickness, e.g. 15 m/min for 25 mm thickness and 150 m/min for 2.5 mm thickness.
2. Stationary oscillating moulds are unable to cope with such high speeds - the travelling mould that accompanies the product during its withdrawal is the solution. Hence, belts and rolls are the best candidates for these new technologies.
3. Feeding of molten steel should be gentle to avoid splashes which would lead to poor surface quality. Molten steel pretreatment, dynamic control of temperature, and preventing reoxidation and renitrogenation by air are essential to ensure satisfactory quality.

4. Surface and internal quality must be irreproachable since there is no chance to correct defects in the cast sections. The geometry of the product should be adequate: flatness, longitudinal and transverse profiles and width must be controlled.
5. At the exit of the mould the cast product should be easily stripped from the mould surface.
6. For thin slab casting, the surface temperature over the entire strand dimension should be kept high enough to allow subsequent hot rolling when necessary.
7. Comprehensive production planning and quality control systems for casting various types of steels with properties equal or superior to those produced conventionally must be ensured.

The various type of near-net-shape casters can be classified in three categories:

1. Stationary Mould Casters
2. Travelling Mould Caster
3. Spray Deposition Caster

### 2.1.1 Stationary Mould Casters

These designs are based on technology similar to that of conventional continuous steel slab caster but are designed for product thickness from 40-70 mm, widths upto 1.6 m and at a speed of 5-6m/min. The various stationary mould designs are descripted

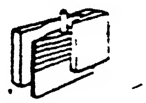
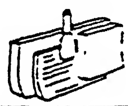
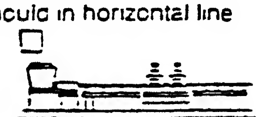
| Process | Manufacturer/ operator | Technical data | Product |
|---|---|---|---|
| Stationary mould  | SMS Buschhutten | Thickn.: 40-60 mm<br>Width: 1600 mm<br>$v_G$ 6 m/min<br>750,000 t/a | Thin slab<br>Usual hot strip grades |
|  | SMS/Nucor Corp Crawfordsville (II 1989) | | |
| Stationary mould  | MDH/MRW Huckingen | Thickn. 40-70 mm<br>Width 1600 mm<br>$v_G$ 6 m/min | Thin slab<br>Usual hot strip grades |
| Stationary mould | Danieli<br>Udine | Thi: 28 50 mm<br>Wi: 1600-1750 mm<br>$v_G$: 6 m/min | Thin slab<br>Strip |
| | Danieli<br>Feng Lung Steel Factory<br>Taiwan | Thickness 75 mm<br>Width 1220 mm | Thin slab |
| Stationary mould in horizontal line HCC  | MDH/Bosch-gottharcshutte Siegen | Thickn. 40-120 mm<br>Width. 450 mm<br>$v_G$. 4 m/min<br>100,000 t/a | Thin slab<br>All steel grades |
| Mould car  | British Steel Corp Teesside Labs | Thickness 75 mm<br>Width 500 mm<br>$v_G$ 10-20 m/min | Thin slab<br>Plain carbon steel |

Fig. 2.1 Stationary Mould Casters 4

in the Fig. 2.1.[4] Most of these mould caster are vertical with oscillating movements. In order to avoid metal feeding problems, the upper mould section is made wide enough so that the refractory tube from the tundish can be accommodated. One of the following methods can be utilized to reduce the final thickness of the strand which is still not completely solid.

a. An oval casting section with reduction below the mould

b. A partially oval section with reduction below the mould

c. A flat section gradually reduced over the mould's full length

d. A rhombic section gradually reduced in the upper part of the mould

e. A 'bellied' section gradually in the upper half of the mould incorporating movable narrow faces to compensate for the width and increase experienced during the thickness reduction

SMS Schloemann Siemog have reported the use of funnel shaped stationary mould with a specially contoured submerged nozzle to prevent the reoxidation in their 1985 pilot plant for the slab casters. A high casting speed of 6 m/min and mould oscillation of 400 cycles/min at a stroke length of 4-8 mm has been tested for producing all types of steels that are conventionally castable. A low melting mould powder is used. MDH and MRW of FRG have announced the development of a thin slab caster of 40-70mm thickness and 1200 mm width with narrow submerged nozzle, vertical

curved mould with parallel broad faces to guide the strand vertically in the upper part of the mould and tangentially at the lower mould region and adjustable mould width. The caster can also be operated in dry condition without the water spray. Direct hot rolling to 10 mm has also been tested. In all these stationary mould processes, high mould friction is the limiting factor. Therefore, casting speeds are limited and so is the production rate.

### 2.1.2 Travelling Mould Casters

The aim of these caster is to minimise the interaction between the mould wall and the cast product which is a major draw back in the earlier mentioned processes for casting thin sections at high speed. These caster require no lubrication i.e. (mould powder) but for heat flow considerations some coating is required on the moving mould. Some of the casters in this category are shown in Figs. 2.2 to 2.4.

#### 2.1.2.1 Twin Belt Thin Slab Casters

Some of the thin slab casters in this category are shown in Fig. 2.2. Petry and Platek[9] have studied the Hazelett twin belt caster in detail which was originally designed for non-ferrous metals. The mould consists of top and bottom carriages - each supporting, tensioning, and transporting a water cooled, thin steel belt. The top carriage can be raised to permit belt changing and mould maintenance. Each carriage has grooved pulleys which simultaneously transports and guides the belt and provides a

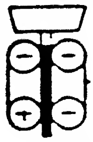
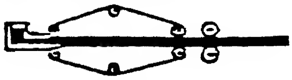
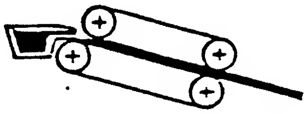
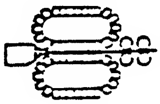
| Process | Manufacturer/ operator | Technical data | Product |
|---|---|---|---|
| 2 travelling belt moulds, vertical  | Nippon Steel Corp | Thickness 50–80 mm<br>Width 600 mm<br>$v_c$ 4 m/min | Thin slab |
| 2 travelling belt moulds horizontal  KCC = Kawasaki Horizontal Continuous Caster | Kawasaki Steel Corp<br>Chiba Research Centre | Thickness 10–30 mm<br>Width 100–150 mm<br>$v_c$ 0.7–12.5 m/min | Strip<br>Low-carbon steels<br>Si-steels<br>Stainless steels |
| 2 travelling belt moulds inclined  Hazelett | Hazelett/<br>Sumitomo MI ·<br>Sumitomo HI<br>Kashima | Thickness 40 mm<br>Width 600–1300 mm<br>$v_c$ 2–8 m/min<br>600 000 t/a (1300 mm) | Thin slab<br>Al-killed steels<br>Stainless steels |
| | Hazelett/<br>Nucor Corp<br>Darlington S C | Thickness 25–38 mm<br>Width 1300 mm<br>$v_c$ 1.5–8 m/min<br>500 000 t/a (1300 mm) | Strip<br>Carbon steels |
| | Hazelett/<br>Krupp Industrietechnik<br>Bochum | Thickness 70 mm<br>Width 180 mm<br>abandoned | Thin slab |
| | Hazelett/<br>Bethlehem Steel +<br>US Steel<br>Universal Pa | Thickness 12–25 mm<br>Width 1830 mm<br>interrupted/abandoned | Strip |
| 2 travelling caterpillar moulds horizontal  | Kobe Steel<br>Nippon Kokan | no details known | |

Fig. 2.2 Twin Bell Thin Slab Caster[4]

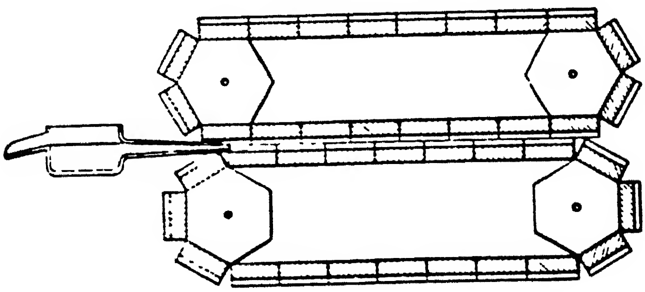


Fig. 2.3 Hunter-Douglas Continuous Casting[10]

longitudinal tension. The thickness of the casting is controlled by interchangeable carriage spacers and can vary between 19 mm to 76 mm. The width of the casting controlled by spacing the metallic side dam blocks which are carried on the steel straps and are transported with the belts. The casting angle can be changed from $0^\circ$ to $20^\circ$. For aluminium, however, only $6^\circ$ inclination to horizontal is necessary. The mould cavity is formed by sandwiching the edge dam block between the upper and lower belts. The top and bottom belts are water cooled with high pressure water jets from the front end of the caster and low pressure water in other regions. For heat extraction from the metal the mould belt are coated with some powder and parting agent so that the slab gets separated from the mould at the exit. The stock from this caster is fed to a slightly lower speed rotating pinch roll which accommodates constant compression during the total solidification. The description of the Hunter Douglas process, as used in the United States, is shown in the Fig. 2.3.[10] This machine was specifically developed as the first stage in the production of strip for Venetian blinds. The strip produced was 178 mm wide and 25 mm thick. The alloy used was Al-Mg-Si alloy produced by water cooled moulds and emerges at the temperature of 450 to 500°C and it was suitable for hot rolling on a small mill.

### 2.1.2.2 Moving Belt with 1 or 2 Rollers[4]

Production of castings which are near to the final product thickness becomes difficult in rotating mould belt because the

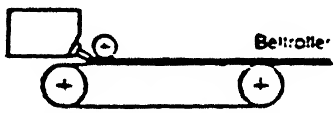
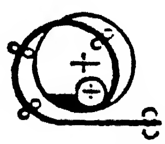
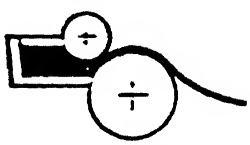
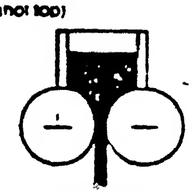
| Process | Manufacturer/ operator | Technical data | Product |
|---|---|---|---|
| 1 travelling casting belt and 1 roller   DeSC-Process Demag Strip Casting | MDH/MSA Belo Horizonte (I 1988) | Thickness 5–10 mm<br>Width 900 mm<br>$v_c$ 25-50 m/min<br>750.000 t/a | Strip<br>All steel grades |
| Inside-The-Ring  | Jones + Laughlin (now LTV Steel) Pittsburgh (1967–1975) | Thickness 5 mm<br>Width 380 mm<br>$v_c$ 7.5 m/min | Strip |
| Twin roller (top roller)  | Kobe Steel Amagasaki | Thickness 1–2 mm<br>Width 260 mm | Thin strip<br>Stainless steels |
| | Nippon Metal | Thickness 1–4 mm<br>Width 315/650 mm | Thin strip<br>Stainless steels |
| | Krupp Stahl AG | Thickness 1–4 mm<br>Width | Thin strip<br>Stainless steels |
| | Nippon Yakin | Thickness 6 mm<br>Width 150 mm | Strip<br>Stainless steels |
| Twin roller (not top)  | Ishikawajima HI/ Nippon Kokan | Thickness 2–6 mm<br>Width 400 mm<br>$v_c$ 25 m/min | Strip<br>Thin strip<br>Carbon steels<br>Stainless steels |
| | Hitachi Zosen Corp | Thickness 5–10 mm<br>Width 300 mm | Strip |

Fig. 2.4 Moving belt with 1 or 2 Rollers[4]

problem of feeding molten metal to the mould becomes more and more accurate as the desired strip thickness decreases. The problem may be over come by employing one or two rollers in place of a moving belt. Fig. 2.4 shows different type of casters in this category which have been tested on laboratory or pilot plant scales around the world.

### 2.1.3 Twin Roll Casters[11-17]

In these casters liquid metal is fed between the two rotating rolls which are internally water cooled. The speed of rotation of the drum is the critical parameter which governs the thickness of the strip produced. This process has been undergoing series of improvements over the past few years. One of the primary reasons for the success of the process is the use of unique tip assembly between the two rolls. The nozzle through which metal is fed on to the rolls is made up of high strength machinable refractory material. The desired casting speed is controlled with relation to roll speed, temperature of head box and furnace and metal head level. One problem with this process is the low production rate. Also, it needs some metal preparation. The mechanical properties of products are low. Metal cleanliness is also cruicial for grain refining. Sticking of cast sheet to the roll shell, obstruction of the liquid metal flow from the feed tip and uneven metal edge are some of the major problems. The typical operating conditions of this caster

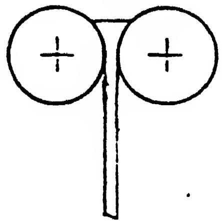
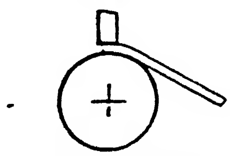
| Process | Manufacturer/ operator | Technical data | Product |
|---|---|---|---|
| Twin roller  | Nippon Steel Corp | Thickness 1 mm<br>Width 200 mm | Thin strip<br>Stainless steels |
| | Nisshin Steel + Hitachi Corp | Thickness < 5 mm<br>Width 200 mm | Thin strip<br>Stainless steels |
| | Kawasaki Steel Corp | Thickness 0.5 mm<br>Width 100 mm | Thin strip<br>Sr steels |
| | Armco + Inland Steel + Weirton Steel + Bethlehem Steel | Thickness < 5 mm<br>Width 300 mm | Thin strip |
| | Clecim/Irsid | Thickness 2-10 mm<br>Width 200 ÷ 850 mm | Strip<br>Thin strip<br>Stainless steels |
| | DEC/British Steel Corp | Thickness 3 mm<br>Width 400 mm | Thin strip<br>Stainless steels |
| | CSM | Thickness<br>Width 300 mm | Thin strip<br>Unalloyed steels |
| | Voest-Alpine | Thickness 2-8 mm<br>Width | Strip<br>Thin strip |
| | Thyssen Grillo Funke - IBF Aachen | Thickness 01-2 mm<br>Width 150 mm | Thin strip<br>Sr steels |
| | MPI fur Eisenforschung Dusseldorf | Thickness 1 mm<br>Width 100 mm | Thin strip<br>Sr steels |
| Single roller  | Armco + Westinghouse Middletown | Thickness 08-3 mm<br>Width 75 mm | Thin strip |
| | Allegheny Ludlum | Thickness 1-2 mm<br>Width 300 mm | Thin strip<br>Stainless steels |

Fig. 2.5 Single and Twin Roll Caster[4]

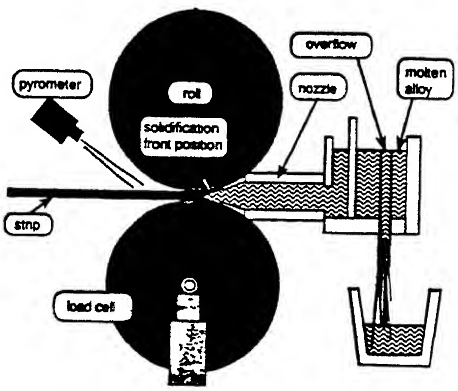



Fig. 2.6 Schematic Configuration of the Horizontal Twin-roll Caster[12]

Thickness range is from 5 mm to 8 mm

Nozzle width is 4 mm

Roll gap setting is 5 to 6 mm

Temperature of the water at outlet is 8-10°F

Essadiqi,E. et al.[12] have studied the horizontal twin roll machine as shown in Fig. 2.6, for aluminium and its alloys. The twin roll were made of 4340 steel with no water cooling. The radius and width of the rolls were 300 mm and 100 mm. The process was controlled by the speed of the rolls which was decreased from 15 rpm until a solid strip was produced. The chemical composition of the Al-Si alloy which was casted is given in Table 2.1. The physical properties of the cast alloy and roll material are shown in the Table 2.2. The cast strip was 3-5 mm in thickness and 100 mm in width. 150 kg of aluminium alloy was melted in an induction furnace. The melt was poured into tundish and injected into the twin roll caster through the refractory nozzle. The casting speed was 2 to 9 rpm depending on the strip thickness and the contact angle which was set in the range of 10 to 20 degrees is given in Table 2.3.

In order to determine the yield strength, the ultimate tensile strength and the elongation of the as cast A356, the tensile test was performed on three longitudinal and transverse direction of the strip, sample was taken and the test were performed according to the ASTM standard. The temperature of the roll surface was measured by means of two chrommel alumel

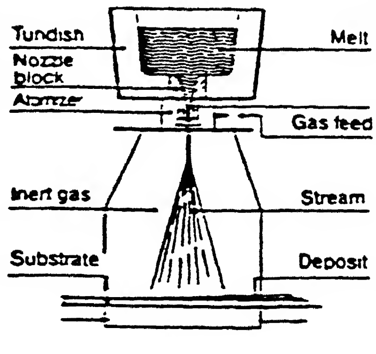
thermocouples that were inserted 2 mm below the roll surface.

### 2.1.4 Single Roll Caster

A brief description of such a caster is already given in Chapter 1. This type of caster is a typical application of a general class of processes known as the Melt Drag Processes. Figure 2.5 gives the present status of Roll Casters for producing steel strips/sheets.

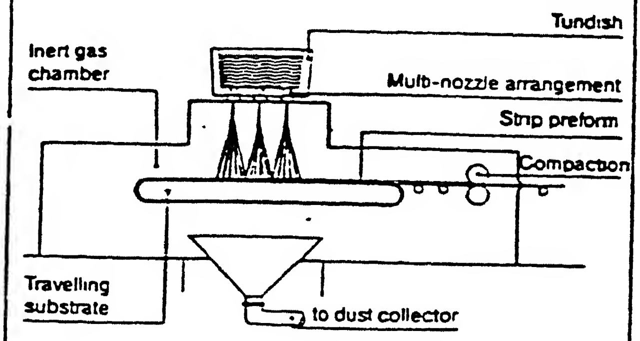
### 2.1.5 Spray Deposition Casters[4]

Continuous metal spray deposition is a new primary shaping process that permits casting high quality products and it can also be employed to produce products of varied compositions as well as a wide variety of different shapes - strips, tube, blanks, round billets forging blanks etc. In addition to homogeneous semifinished materials, composite materials can also be produced. Figure 2.7 shows the design of the caster.[2] In this type of caster a stream of liquid metal, emerging from the single refractory nozzle, built into the bottom of a tundish is gas atomized. The atomized droplets moving at high velocity, are directed to and impinge on a moving belt constructed of ceramic blocks. While moving from the gas atomizing unit to the belt the particles are cooled to just above the solidus temperatures. On impinging the substrate a thin film is formed from the remaining residual liquid in the semi-liquid droplets, which then dissolves the boundaries of the solid droplets, forming a uniform pore free layer. Depending on the shape and the movement of the substrate surface,



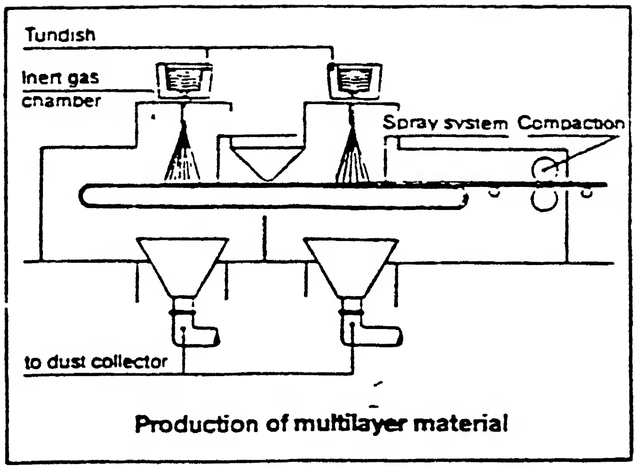

Principle

a

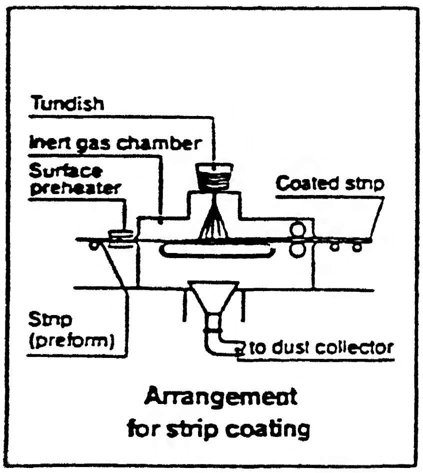



Multi-nozzle arrangement for strip production

b




c




d

Fig. 2.7 Spray Deposition Process 4

**Table 2.1: Chemical Composition of A356 Alloy Wt%[12]**

| Al | Si | Fe | Mg | Mn | Zn | Cu |
|---|---|---|---|---|---|---|
| remaining | 7.39 | 0.33 | 0.48 | 0.14 | 0.24 | 0.19 |

**Table 2.2: Physical properties of A356 Al alloy and Roll Material 4340.[12]**

| Material | Properties | |
|---|---|---|
| A356 Al alloy | Density $\rho$ ($kg/m^3$) | 2600 |
| | Specific heat $C_p$ (J/kgK) | 1100 |
| | Solidus $T_s$ (°C) | 555 |
| | Liquidus $T_c$ (°C) | 615 |
| | Thermal conductivity k (W/mK) | 221 |
| | Latent heat of fusion $H_f$ (kJ/kg) | 389 |
| 4340 Steel | Density $\rho$ ($kg/m^3$) | 7800 |
| | Specific heat $C_p$ (J/kgK) | 585 |
| | Convection coefficient ($W/m^2K$) | 20 |
| | Emissivity $\varepsilon$ | 0.6 |
| | Thermal conductivity k (W/mK) | 36 |

**Table 2.3: Experimental Condition for the strip casting of A356[12]**

| Contact Angle Degrees | Liquid Temperature °C | Speed rpm |
|---|---|---|
| 10 | 630 | 7.20 |
| | 630 | 6.00 |
| | 630 | 4.70 |
| | 630 | 3.37 |
| 20 | 625 | 8.60 |
| | 625 | 6.00 |
| | 635 | 5.46 |
| | 625 | 3.95 |
| | 635 | 3.23 |
| | 625 | 2.40 |

different geometric shapes can be produced.

## 2.2 MATHEMATICAL MODELLING OF A SINGLE ROLL CASTER

Chopra and Niessan[18] were among the first investigators to model the single roll strip casting process for low melting point metals and alloys. In the process modelled by them, a pool of molten metal is kept in a reservoir and the caster drum is rotated through it. The principal model equation is a transient heat conduction equation which is solved using a control volume based finite difference method along with the boundary conditions which are specified based on experiments carried out on a stationary system. Using a simulation model, Pimputkar et al.[3] have shown that the strip thickness is strongly affected by the drum speed, the melt pressure, the metal head in the tundish and the stand off distance between the tundish and the drum, while the orientation of the tundish nozzle, its size, superheat of the melt and substrate temperature and material only weakly affect the final strip thickness.

In the recent past, Mehrotra and coworkers[19-24] have attempted to formulate the mathematical models for the process based on considerations of heat transfer and solidification and fluid flow, respectively. First of these models, which is referred to as the macroscopic enthalpy balance model, is based on overall enthalpy balance and growth of the solidification front.[19] The growth of the solidified steel shell on the caster drum surface is established using Stefan's heat flow deduction. The so

called microscopic heat balance mode is based on overall and segmentwise heat balances, and growth of the solidification front.[21] Three different heat balance zones are visualized: (i) the solidification zone, (ii) the strip cooling zone, and (iii) the no-strip zone. Segmentwise heat balance is carried out by dividing the solidifying steel strip and the caster drum into several small interconnecting nodes/segments. The basic model consists of one algebraic and two partial differential equations which are coupled. The model provides interrelationships among the growth rate of the solidifying strip and the complete temperature fields in the caster drum and the strip and the process variables.

Model based on fluid mechanics considerations only, identifies four regions containing liquid metal: (i) straight-vertical region of the tundish, (ii) elbow region of the tundish, (iii) converging chamber of the nozzle, and (iv) liquid metal pool.[18] The fluid flow is considered separately in each of these regions. As the model attempts to highlight the fluid mechanics aspects of the process only, effects of thermal parameters and variables, e.g. various heat transfer coefficients relevant to the process, superheat of the metal, release of latent heat on solidification, etc. are lumped together in a single empirical coefficient.

The two types of models, developed by Mehrotra and coworkers,[19-22] and discussed above, suffer from some drawbacks.

For instance, the heat balance models assume constant temperature in the liquid pool and ignore any fluid flow in the region, which truly speaking may result in a variable heat transfer coefficient along the melt/strip interface. The velocity field in the pool region will result in a temperature field making the assumption of constant liquid metal temperature in the pool erroneous. On the other hand, the model based on fluid mechanics considerations, ignores the important heat transfer related phenomena.

Comparison of results predicted by these two types of models clearly indicates that while the fluid mechanics based model over predicts the final sheet thickness, the heat transfer based models have a tendency to under predict. Mallik and Mehrotra[23] have divided the process into four distinct zones: (i) liquid metal reservoir, (ii) liquid metal pool, (iii) solid strip zone, and (iv) caster drum, and developed a model based on fluid flow and heat transfer considerations. The principal model equations are formulated using a control volume approach and setting up equations representing balances of mass, momentum and energy for these zones. These equations, which are coupled by various interfaces, are solved using an iterative finite difference technique.

Although the latter mode is superior to earlier models, it is based on many gross approximations. To mention a few, for instance, the fluid flow in the molten metal pool is described by one dimensional Couette flow while in reality it may be two

dimensional and recirculating. Shamsi and Mehrotra[24] have recently formulated a mathematical model by relaxing many of the assumptions in the previous model. The fluid flow phenomena in the molten metal pool are characterized by vorticity and stream functions. More realistic boundary conditions are used. Beside predicting the effects of various operating variables on the process performance the model also predicts the velocity and temperature fields in the molten melt pool.

# CHAPTER 3

# DESIGN AND FABRICATION OF SINGLE ROLL CONTINUOUS STRIP CASTER AND ACCESSORIES

The design and fabrication of the single roll strip caster was initiated by Mehrotra and coworkers.[19-24] The fabrication of the caster was, however, completed and the caster was made fully operational during the course of the present investigation. A brief description of the caster design and its assembly is presented in this chapter.

## 3.1 SINGLE ROLL STRIP CASTER

A schematic diagram of the caster assembly is shown in Fig. 3.1. where as Fig. 3.2 is a photograph of the caster in operation. The main components of the caster include:

(i) Tundish/Reservoir

(ii) Caster Drum Assembly

(iii) Water Spray System to Cool the Caster Drum

(iv) Knife Edge

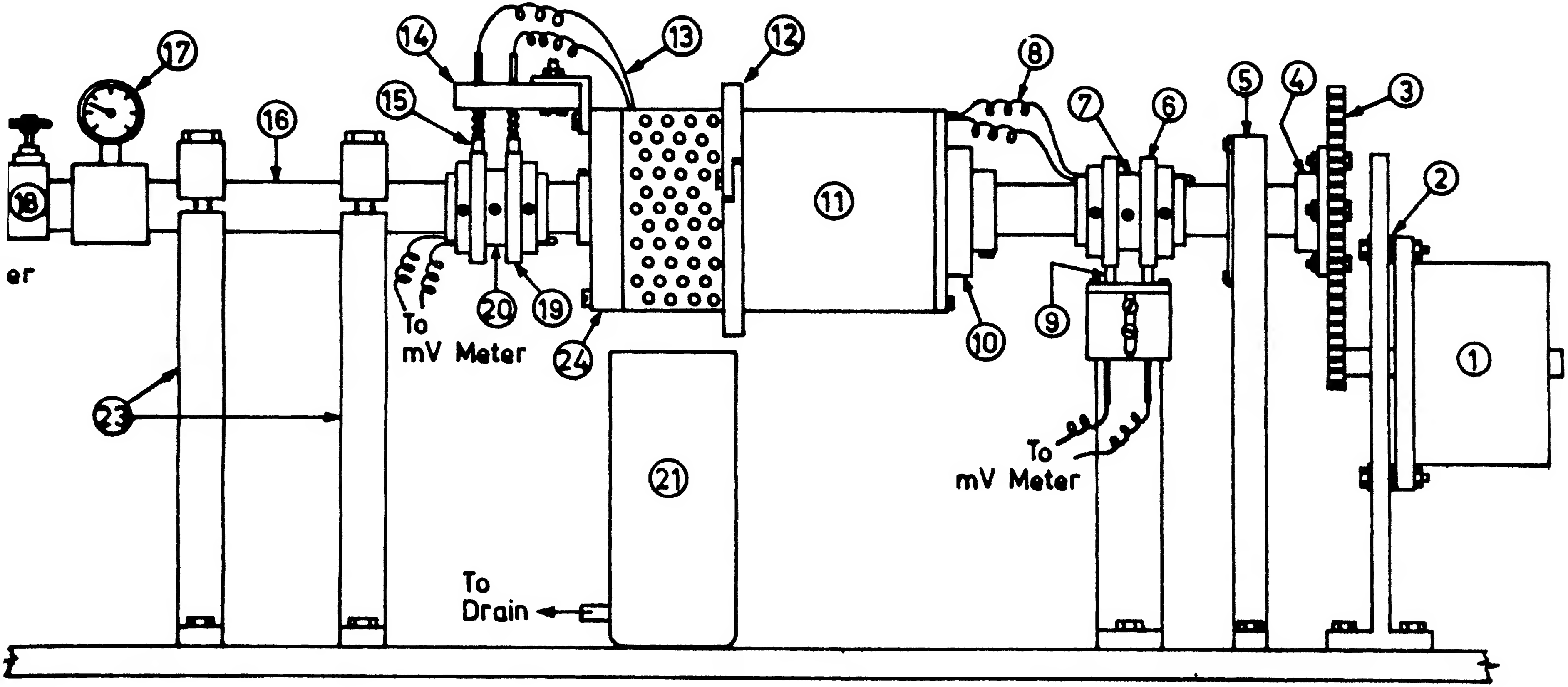
(v) Stepper Motor to Rotate the Caster Drum

(vi) Microprocessor Based Control System

(vii) Gear Assembly to Change the Speed of Rotation of the Caster Drum

(viii) Thermocouple Assembly

(ix) P.C. Based Data Acquisition System




① Stepper Motor ② Rubber Washer ③ Reduction Gear ④ Brass Coupling ⑤ Ball Bearing Holder
⑥ Copper Ring (Rotating) ⑦ Teflon Sleeve (Rotating) ⑧ Thermocouple ⑨ Carbon Brush
⑩ Brass Flange ⑪ Copper Drum ⑫ Brass Ring ⑬ Thermocouple ⑭ Teflon Plate
⑮ Carbon Brush ⑯ S.S. Tube ⑰ Pressure Meter ⑱ Valve ⑲ Copper Ring (Stationary)
⑳ Teflon Sleeve (Stationary) ㉑ Water Collector Tank ㉒ Brass Flange ㉓ M.S. Stand
㉔ Cover Plate (Brass).

Fig. 3.1 Schematic Diagram of Strip Caster Assembly

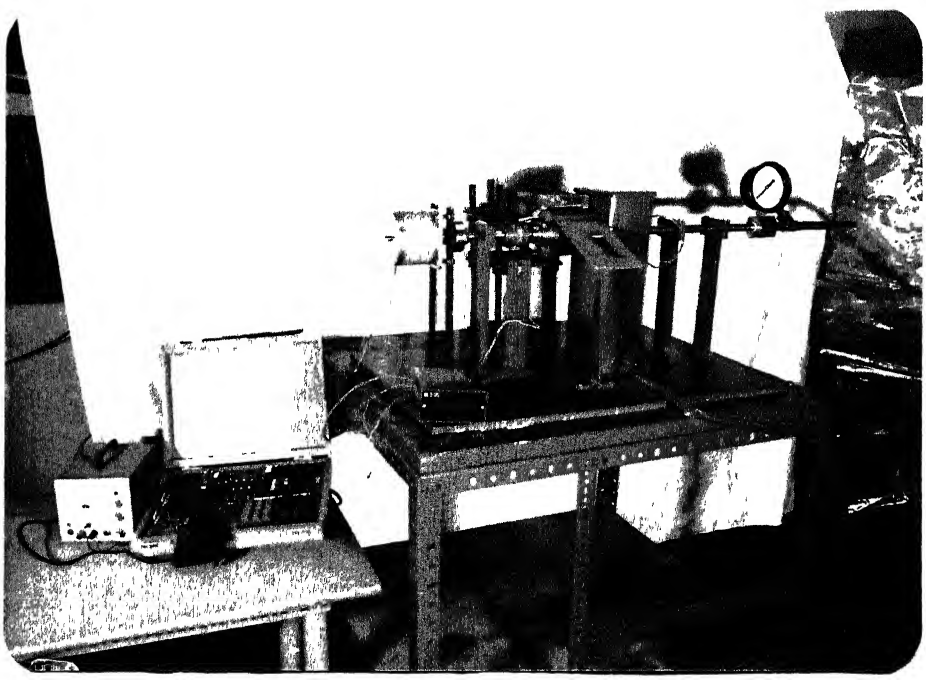


Fig. 3.2 Photograph of the Caster in operation

### 3.1.1 Tundish/Reservoir

Tundish primarily acts as a reservoir to hold molten metal, and feeds it on to the rotating casting drum in a controlled manner. The rate of flow of the metal to the drum, which is determined by the rate at which the metal is removed in the form of the solidified strip is controlled by controlling a constant metal head in the tundish. Tundishes used in this investigation are made out of fireclay bricks. Figure 3.3 shows a tundish with typical dimensions. The tundish wall facing the drum has the same concentric profile as that of the drum. It has a rectangular opening at the bottom of this concentric face which acts as an outlet for the molten metal. The width of this rectangular opening has been used as a variable in this investigation and has been varied the width between 10 to 20 mm. The tundish is placed very close to the caster drum without touching it to avoid scratching of the drum surface. At the same time it is ensured that the gap between the drum surface and the tundish is not large enough to lead to the leakage of the molten metal through this gap.

The tundish is placed on a rectangular cast iron platform which is supported on four threaded rods, one each on each corner of this platform. Vertical position of the platform can be varied by adjusting the position of four hexagonal nuts, one in each rod, on which the platform rests.

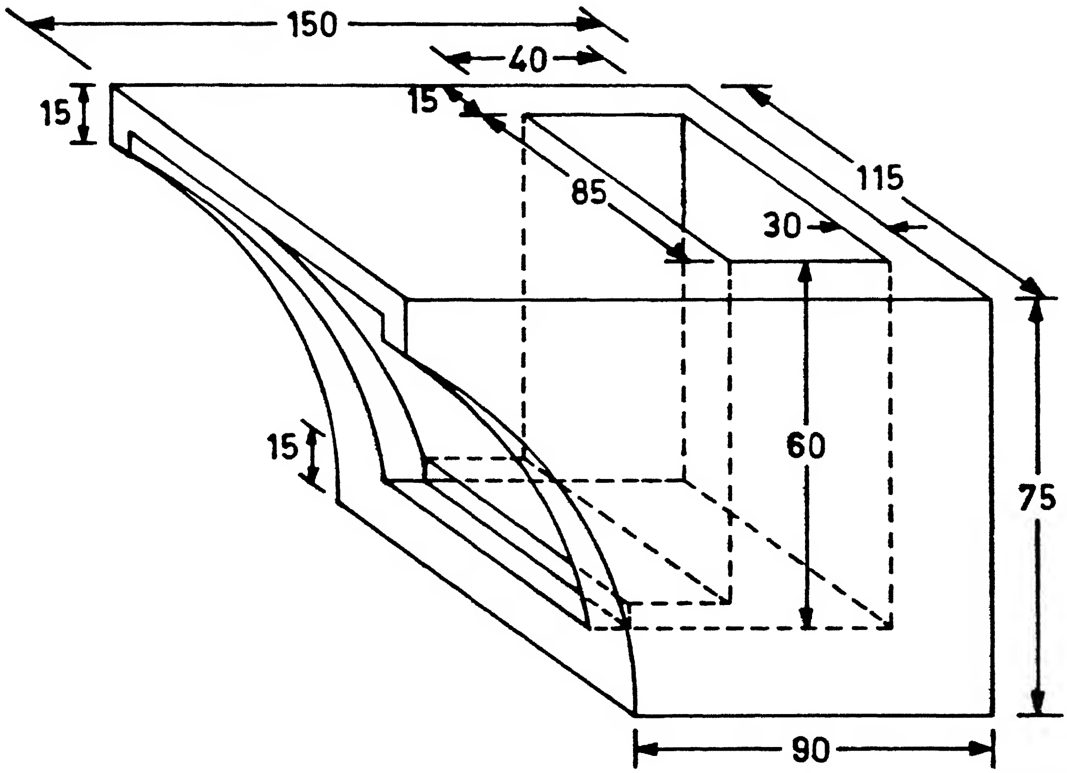



Fig. 3.3 Schematic sketch of Tundish

### 3.1.2 Caster Drum Assembly

The caster drum is made of high purity copper (99.9% purity). It is a hollow cylinder with both ends open. The outer diameter of the caster drum is 112 mm. The total length of the drum is divided into two parts:

1. The caster drum portion
2. The water outlet portion

The total length of drum is 177mm out of which 112 mm represents the length of the caster drum portion on which the strip is cast. The remaining length (65mm) is drilled with holes on its surface and provides an outlet for the spray water. The inner surface of the drum towards the water exit end is tapered, as shown in Fig. 3.4, to facilitate the flow of water. The thickness of the drum wall is 7.5 mm. Both ends of the drum are fitted with brass flanges. One end of the caster drum is connected to the shaft of the stepper motor through a gear assembly which rotates the drum at a prespecified speed of rotation while the other end of the drum is connected to a water pipe line which also holds the water spray assembly inside the drum. The caster drum and the water outlet portion of the drum are separated on the outer surface by a brass ring so that the exit water does not come in contact with the molten metal or the solidifying strip at any time. The water outlet portion of the caster drum is enclosed in a casing such that all the exit water is collected and finally drained out through a pipe.

### 3.1.3 Water Spray System to Cool the Caster Drum

Water spray assembly consists of 4 nozzles placed at right angle to each other and in two rows as shown in Fig. 3.4 and Fig. 1.2. The water spray cover almost the entire surface area of the caster drum to ensure its uniform cooling. The spray nozzle are specially designed such that each nozzle generates a fully developed water cone with cone angle of about $70^{\circ}$. The nozzles are fitted through the manifolds on the horizontal stainless steel pipe which passes through the brass flange on one of the open ends of the caster drum. This pipe remains stationary even when the drum is rotating.

### 3.1.4 Knife Edge

The knife edge, made of aluminium sheet, is fixed on to the platform on which the cast sheet moves after solidification (see Fig. 1.2). This platform is on the other side of the caster drum. The main function of the knife edge is to peel off the solidified strip from the caster drum. The position of the knife edge on the drum can be adjusted through its mount by giving it required horizontal and vertical movements.

### 3.1.5 Stepper Motor to Rotate the Caster Drum

The motor used to rotate the caster drum to any specified rotational speed is a Uni-step stepper motor. It runs with 12 volt D.C. supply and can withstand a load of 10 kg. The motor supplied by M/s Unique System of Control Pvt. Ltd., New Delhi, has the following specifications

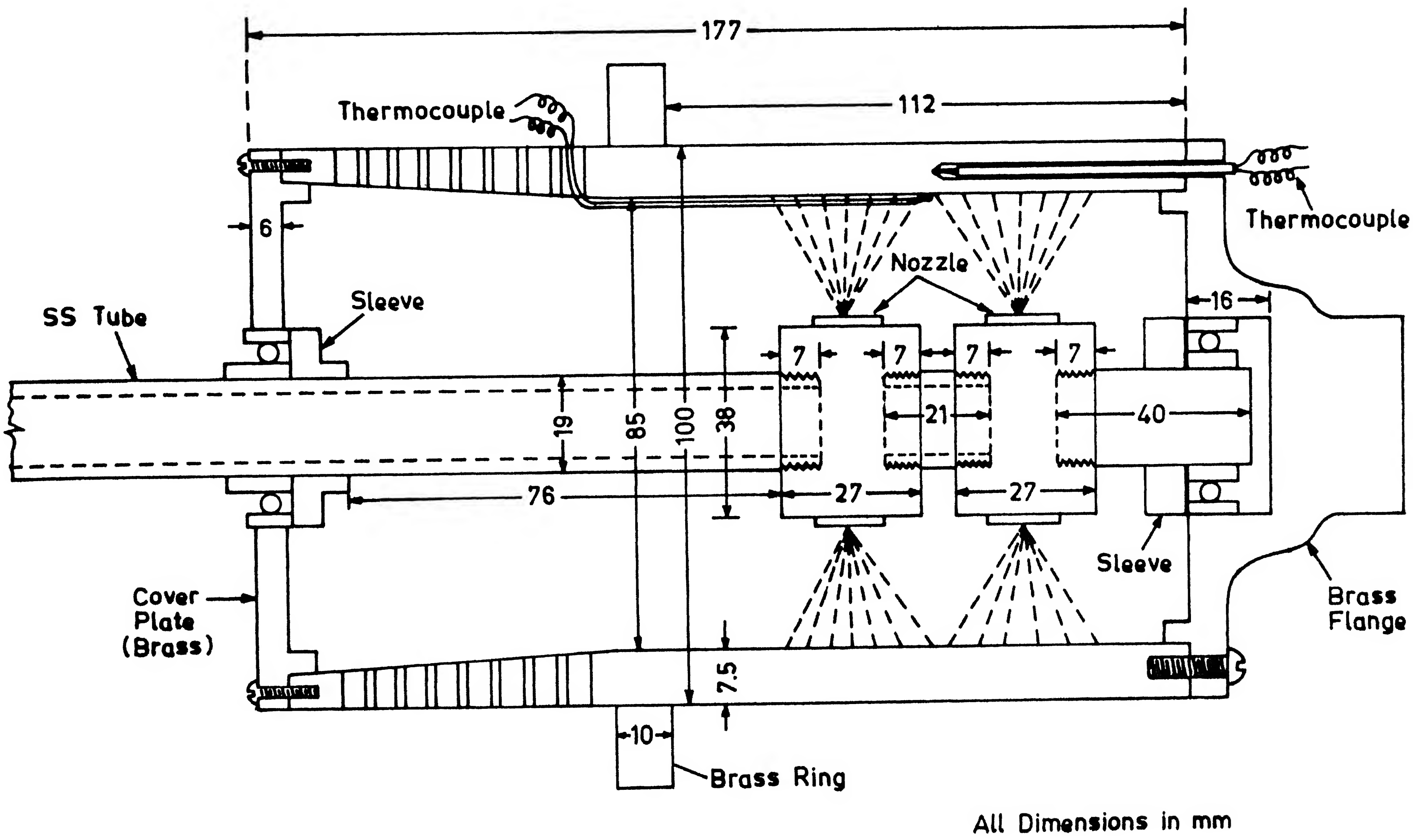



Fig. 3.4 Schematic Diagram of Caster Drum Assembly

4.2 V/ph No. 5521 4.5/Amp. phase

1.8$^\circ$ Step Type 31

The motor can be directly coupled with the caster drum through a shaft or it can be coupled through a gear assembly to obtain wider range of the speed of rotation. Without a gear assembly the motor can give rotational speed variation between 1.5 to 38 rpm

### 3.1.6 Microprocessor Based Control System

The microprocessor kit used to control the stepper motor was supplied by M/s V.M.S, New Delhi. Its specification are given below:

The Kit No. 8085

Total Memory Capacity : 64 K Bytes

Power Supply for the Microprocessor : 6 Volts

The programme to control the speed of the Stepper motor through this microprocessor has been indigenously developed and is given in Appendix I.

### 3.1.7 Gear Assembly to Change the Speed of Rotation of the Caster Drum

As mentioned above also, the stepper motor on its own can give rotational speed variation between 1.5 to 38 rpm only. To carry out experiments at rotational speeds beyond this range a gear assembly has been designed. Two gears with the ratio of 1:3 have been fabricated. The caster drum can be attached with the stepper motor through this assembly in two ways.

1. The stepper motor is connected to the larger gear and the caster drum through the smaller gear as shown in Fig. 3.5a and Fig. 3.5b.
2. The stepper motor is connected to the smaller and the caster drum through the larger gear.

The former arrangement increases the speed of the caster drum three times to that of the stepper motor while the latter arrangement reduces the drum speed to 1/3 of the stepper motor speed. Thus, with the help of the gear assembly range of the rotational speed can be enlarged to 0.5 to 114 rpm.

### 3.1.8 Thermocouple Assembly

Provision is made to continuously measure the temperature of the caster drum wall at two points during the casting. These temperature can be measured using chrommel-alumel thermocouples. The locations at which these measurements can be made are shown in Fig. 3.4. As can be seen, one of these is at the centre of the drum wall at the mid-point along the length of the casting zone while the second location is almost at the inner surface of the drum. It approximates the inside wall temperature of the drum which is cooled with water sprays. The emf generated on the first thermocouple is transferred to a copper ring fitted on a teflon sleeve which moves along with the shaft which rotates the caster drum. From the copper ring the emf is transferred to a stationary carbon bush which, in turn, is connected to a P.C. Based Data Acquisition System. The emf generated on the second thermocouple is transferred to carbon bush mounted on the teflon plate which is

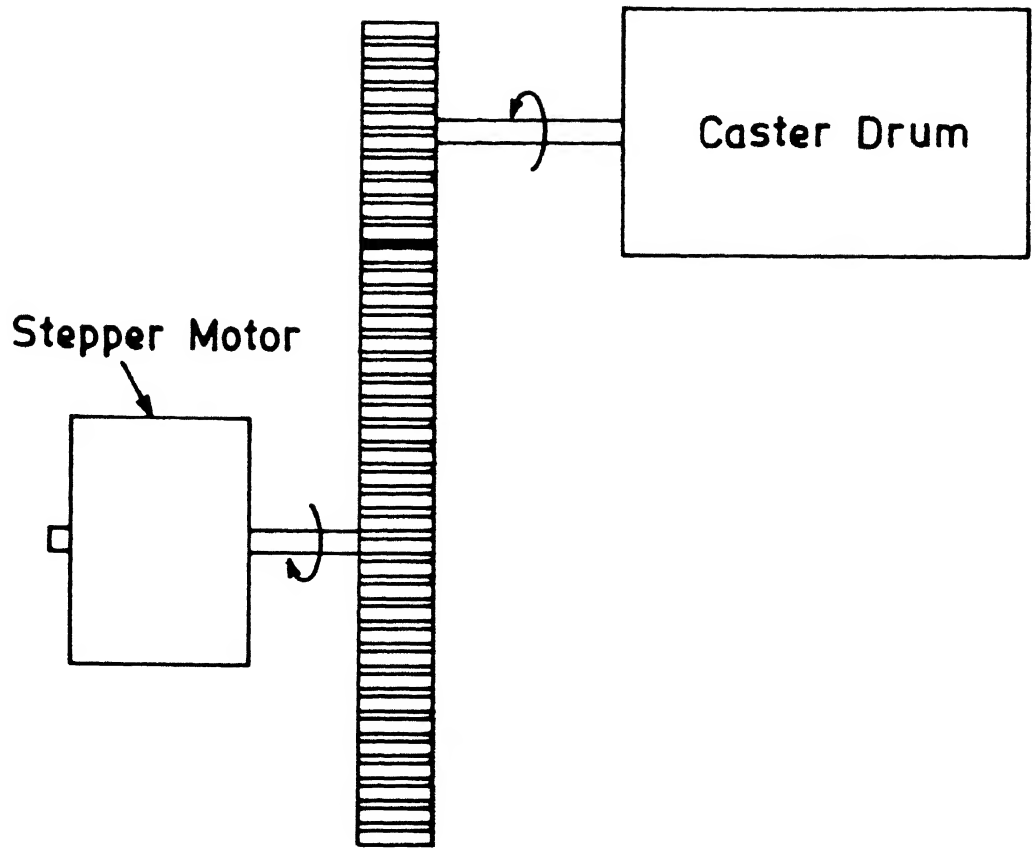



Fig. 3.5a Gear Assembly Motor with larger Gear

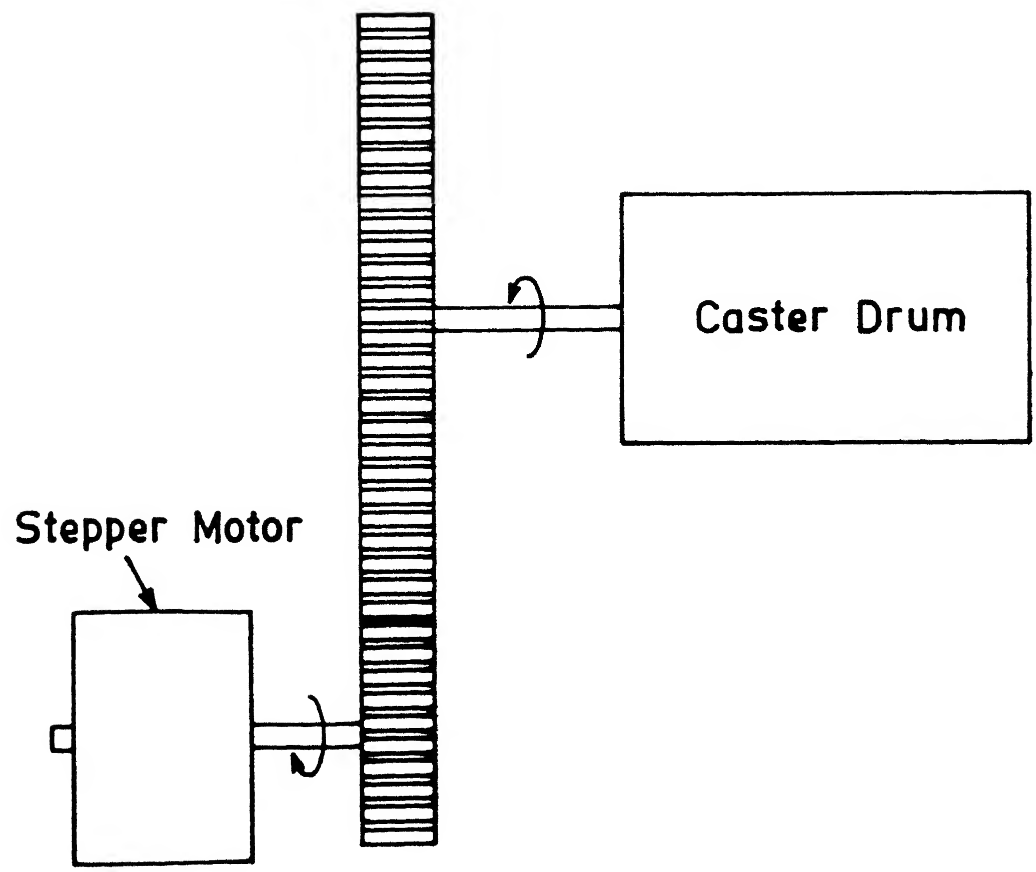



Fig. 3.5b Gear Assembly Motor with smaller Gear

fixed to the end flange and thus rotates along with the drum. The voltage is transferred to the stationary copper ring fitted on teflon sleeve. The leads are connected to P.C. Based Data Acquisition System.

### 3.1.9 P.C. Based Data Acquisition System

This system is primarily designed to record the emf generated by the two thermocouples described above. The main component of this system is a HCL Busy Bee PC to which a PCL 212 thermocouples input card with dual integration type analog to digital converter is connected.

The main features of PCL 212 input card are:

1. The conversion time of emf to temperature is 40 millisecond.
2. Eight thermocouple input channels are available.
3. Different types of thermocouples can be used.
4. It has an optically isolated external triggering mode to stop the conversion.

The thermocouples used in this investigation are chrommel-alumel.

The temperatures are recorded in millivolt. Two of the eight channels are used. The channel '0' is connected to the internal surface of the copper drum while channel '1' is connected to the outer surface of the copper drum.

General Specifications of PCL 212 Input Card

| | |
|---|---|
| Power Requirements | +5V, 350 mA |
| | +12 V, 200mA |
| | -12V, 20 mA |

Dimension 235 mm(L)x180 mm(H)

## 3.2 CASTER ACCESSORIES

The two main accessories required for successful casting include:

1. Melting furnace
2. Crucible/ladle

### 3.2.1 Melting Furnace

A muffle furnace has been designed and fabricated to melt aluminium. The muffle is made of fireclay refractory bricks and has internal dimensions 205x230x230 mm. The furnace is heated through six silicon carbide heating elements of 12.5 mm diameter and 375 mm length. These heating elements are placed in the vertical grooves cut on the inside surface of the muffle which is placed inside a mild steel rectangular shell. The space between the shell and the muffle is filled with fireclay powder while the outer surface of the shell is wrapped with asbestos cloth. The top of the furnace is covered with a refractory lid. The power input to the furnace is from the mains through a variable transformer. The furnace is designed to attain a maximum of about 850°C temperature, and can hold a charge of about 2.5kg molten aluminium.

### 3.2.2 Crucible/ladle

A clay graphite crucible, procured from the local market, serves both as a container to melt the metal as well as a ladle to transfer the molten metal from the furnace to the tundish. The typical dimension of the crucible are given below:

Top diameter :127 mm, Bottom diameter: 76 mm

Height:180 mm

The crucible is fixed on to a mild steel ring to which a mild steel handle is welded (See Fig. 3.6). This handle is wrapped with asbestos cord to make it insulated. This whole assembly can be placed inside the furnace for melting. When the crucible is ready for casting, the crucible is lifted out of the furnace with the help of the handle and the metal is slowly poured into the tundish.

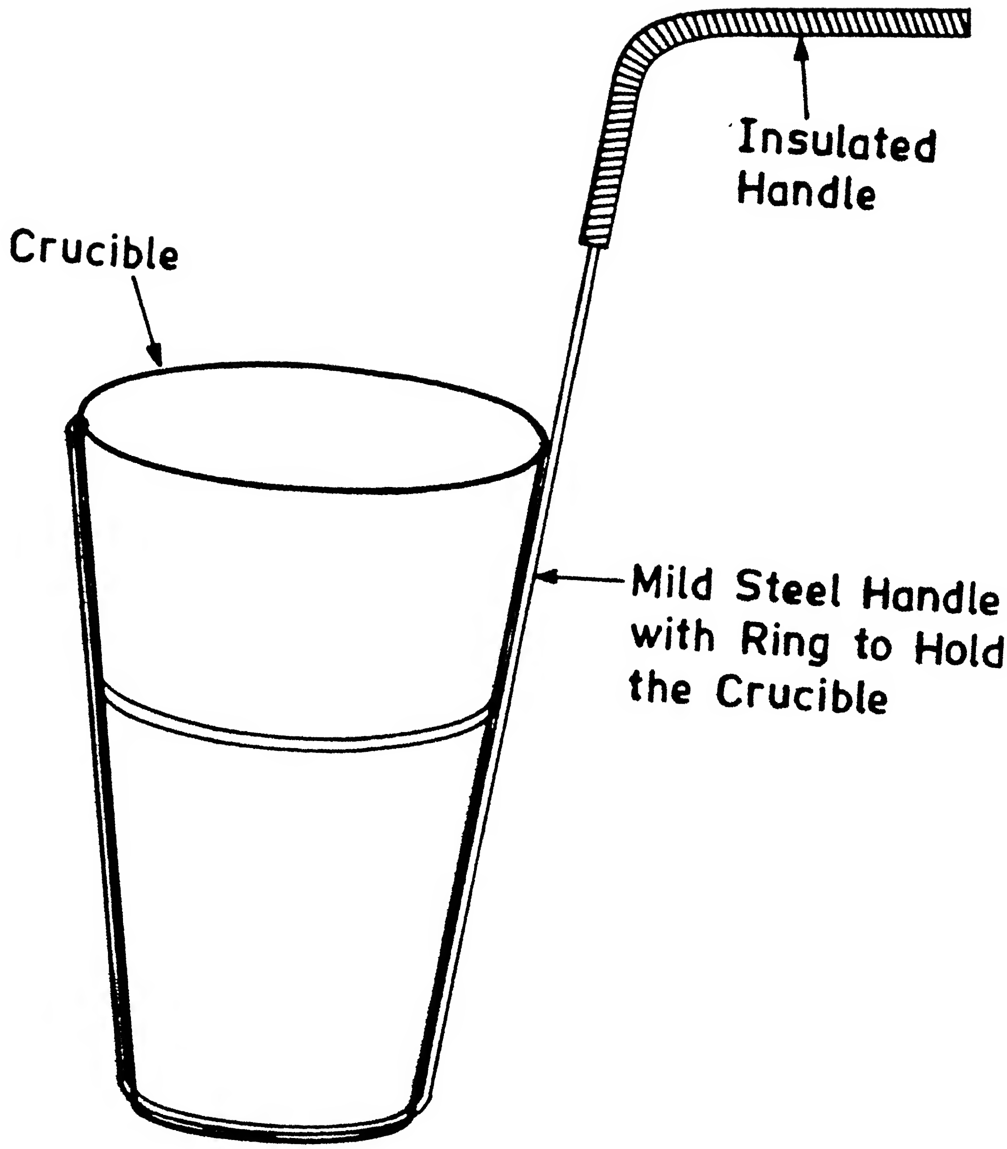



Fig. 3.6 Schematic Diagram of Crucible/ladle

# CHAPTER 4
# EXPERIMENTAL PROCEDURE

As indicated above also the main feature of this investigation has been to produce aluminium strips using the caster, described in the previous chapter, under various operating conditions to study the effect of these variables on the final strip thickness and the strip quality. The main raw materials used include the commercial grade aluminium in ingot form and the fireclay bricks used for making tundishes. Both were procured from the local market.

## 4.1 PREPARATORY STEPS

Before going for the actual casting operation certain initial preparatory steps are required. These are described below.

### 4.1.1 Tundish Preparation

Fireclay tundish used in these experiments lasts on average 3 to 4 runs. Before starting an experiment the condition of the tundish is thoroughly examined for the following:

(a) there should not be any crack any where,

(b) the tundish outlet should be uniform throughout and there should not be any metal sticking on it from the previous run, and

(c) the outer profile of the tundish facing the caster drum should be concentric with it.

In case, any of the above conditions are not being met a new

tundish is fabricated (as per the design discussed in Chapter 3) and used. For each experimental run, the tundish is preheated to minimize any thermal shocking.

### 4.1.2 Adjusting the Height of the Tundish Platform

As mentioned in the previous chapter, the tundish is placed on a cast iron platform the vertical position of which can be adjusted with the help of four hexagonal nuts on which it rests. Before starting an experiment the vertical position of the platform is adjusted depending on the required position of the liquid metal pool with respect to the rotating caster drum. In most of the experiments the platform position was so adjusted that the caster drum first came in contact with the molten metal at an angular position of 20° from horizontal. It was also ensured that the platform was perfectly horizontal to ensure uniform flow of molten metal from the tundish to the metal pool.

### 4.1.3 Gear Assembly Attachment

Gear assembly is used only in those experiments in which the specified speed of rotation of the caster drum is beyond the range obtainable through the stepper motor alone. In such cases depending on whether the desired rotational speed is on the lower side or the higher side the caster drum is attached with shaft of the stepper motor as shown in Fig. 3.5(a) and 3.5(b), respectively.

### 4.1.4 Feeding the Programme to the Microprocessor

The speed of the stepper motor is controlled through the microprocessor. The required rotational speed is obtained by feeding a programme to the microprocessor. To do this, the power supply to the microprocessor is switched on and the numbers, as per the programme (see Appendix I), are entered through the microprocessor keyboard. This is done at the beginning of each experimental run. The programme is tested each time by switching on the stepper motor and measuring the rotational speed of the caster drum with the help of a stop watch. After the satisfactory testing of the rotational speed of the drum the microprocessor is kept on the 'hold' position until such time when the actual casting begins.

## 4.2 STRIP CASTING

Casting of aluminium strips primarily involves two steps:

(i) Preparation of Melt

(ii) Casting

### 4.2.1 Preparation of Melt

As mentioned in Chapter 3, aluminium is melted in muffled furnace using a clay-graphite crucible/ladle. To start an experiment the melting furnace is switched on and the furnace controller is set for 800°C temperature. It takes about 6 hours to reach the set temperature. The charge mainly consists of aluminium ingot, scrap and returns from previous heats. The crucible is charged with a specified amount of aluminium (1.25kg)

and placed inside the furnace after the furnace temperature is reached and stabilized. The top of the furnace is then covered with the furnace lid. When the charge is fully molten it is stirred with an iron rod to homogenize the melt. At this stage 10 gm of a degasser (hexachloro ethane) and 5 gm of a flux (aluminium chloride) are added to the liquid metal and the metal is stirred. After about 15 minutes of this operation the crucible is taken out of the furnace and is placed on an extended platform. The melt is stirred again. The impurities which float at the surface of the melt are then removed with the help of a spoon. The temperature of the melt is continuously monitored during this whole operation with the help of a chrommel-alumel thermocouple. When the temperature of the melt reaches a prespecified value, which depends on the superheat of the melt desired, it is ready for casting.

### 4.2.2 Casting

After the melt is ready, and the preheated tundish is properly positioned on the cast iron platform with respect to the caster drum, the stepper motor is started with the help of the microprocessor. The waterline is switched on and a prespecified water flow rate is set. The caster is now ready for casting. The crucible, holding the molten metal, is manually lifted and the metal poured into the tundish. The pouring of metal is done in such a way that the molten metal level in the tundish reaches the marked level quickly enough and then it remains more or less

constant during the entire casting process. When the metal is poured a molten metal pool is formed in the annular space between the rotating caster drum and the tundish wall. As soon as the drum comes in contact with the molten metal formation of solid strip begins at the drum surface. This strip is gently withdrawn from the pool and brought over the drum surface with the help of dummy bar which in this case is nothing but a bent aluminium piece of the same width as that of the strip. Once the strip comes to the top of the drum it travels on its own. It is separated from the drum surface by the knife edge which also guides it on to the slanted platform. The strip then travels on this platform in continuous length. The casting process is continued as long as the molten metal is continued to be poured from the ladle to the tundish or as long as the strip length does not exceed the platform length. In the latter case the strip without any suport at the bottom tends to hang in air. This results in exerting a back pressure which disrupts the continuous flow of the strip. This, in turn, leads to premature solidification of the molten metal in the liquid metal pool and causes clogging of the tundish opening. Temperature of the caster drum at two points is continuously monitored and recorded through the PC based data acquisition system as described in the previous chapter.

After the casting is completed, the strip is removed from the strand and cooled in air. When the strip is sufficiently cooled down, it is marked with an identification number which specifies

the operating conditions used for this particular casting. Each strip is then examined for its surface finish and the nature of cracks if there any.

The length of the strip is recorded. Its thickness is measured at several positions along its length as well as along its width with the help of a micrometer calliper. The average value of these various thickness measurements is reported as the strip thickness. It may be pointed out that the strip thickness is quite uniform throughout the length and the width of the strip. It generally varies within ± 10% around the average value. Sufficient number of samples are taken out from each casting for its evaluation in terms of its microstructure and its tensile strength properties and also the effects of various hot and cold working and annealing treatments. However, these results are not reported in this thesis as these constitute a part of another separate investigation.

# CHAPTER 5

# RESULTS AND DISCUSSION

Using the experimental procedure described in the previous chapter, several experiments (about sixty) were carried out to examine the effect of various operating variables on the strip thickness produced. The variables and their ranges examined in this investigation are given in Table 5.1. These variables include:

1. Speed of rotation of the caster drum
2. Superheat of molten metal
3. Liquid metal head in the tundish
4. Tundish opening size (Nozzle gap)
5. Standoff distance
6. Cooling conditions prevailing at the inner surface of the caster drum.

To check the reproducibility of our results, several experiments were repeated under indentical conditions. The reproducibility of results has been very satisfactory in almost all cases. The variation is within ± 10% which, considering the nature of the experiments, is quite acceptable. The experimental data points shown in the graphs in this chapter represent the mean value if the experiments has been repeated.

## 5.1 Effect of Speed of Rotation of the Caster Drum

The speed of rotation of the caster drum is perhaps the most critical parameter which affects the strip thickness. Figure 5.1

**Table 5.1 : Process Variables and their Ranges examined in this investigations**

| Sr.No. | Variables | Ranges |
|---|---|---|
| 1. | Rotational speed of caster drum | 1.5 - 38 rpm |
| 2. | Melt of superheat | $30^{\circ}$- $90^{\circ}$C |
| 3. | Metal head in tundish | 10 mm - 40 mm |
| 4. | Nozzle opening | 10 mm - 20 mm |
| 5. | Standoff distance | 10 mm - 20 mm |
| 6. | Water flow rate (gallons per minute) | 0.4 gpm- 0.8 gpm |

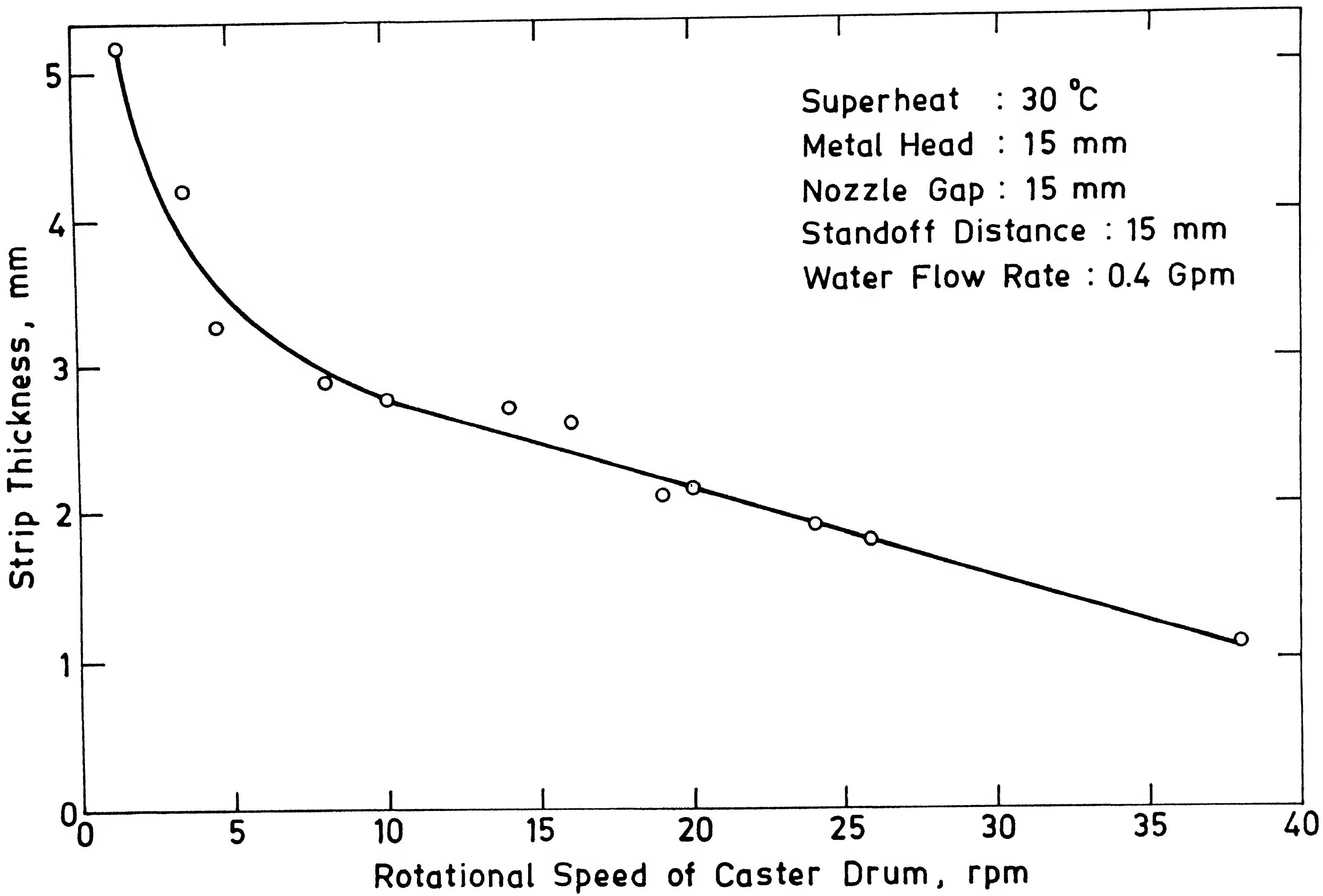



Fig. 5.1 Effect of Speed of Rotation on the Strip Thickness

is a typical plot showing the effect of rotational speed on the strip thickness for a liquid metal head of 15 mm, nozzle gap of 15mm, and the metal superheat of 30°C. The water flow rate in this case was maintained around 0.4 gallons per minute using eight nozzles. It is seen that the strip thickness decreases from about 5.17 mm, to about 1.1 mm as the rotational speed is increased from 1.5 to 38 revolutions per minute. Further, it is to be noted that the effect of increased rotational speed is more in the lower range of rotational speed than that in the higher range. For instance, increasing the rpm from 1.5 to 20 rpm reduces the strip thickness from about 5.0 mm to 2.00 mm whereas when the rotational speed is increased from 20 to 38 rpm the thickness is reduced to only 1 mm.

The reason for increased strip thickness at lower rotational speed is attributed to the larger residence time that the solidifying strip has in the liquid metal pool allowing it to grow thicker. Higher rpm allows lesser residence time producing thinner strips. Thus, there is an inverse relationship between the rpm and the strip thickness.

## 5.2 Effect of Superheat of Molten Metal

The superheat of the melt is defined as the difference in the temperature of the melt and its liquidus temperature. The effect of melt superheat on strip thicknes is seen in Fig. 5.2 in which the final strip thickness has been plotted as a function of melt superheat for three different values of drum rotational speeds

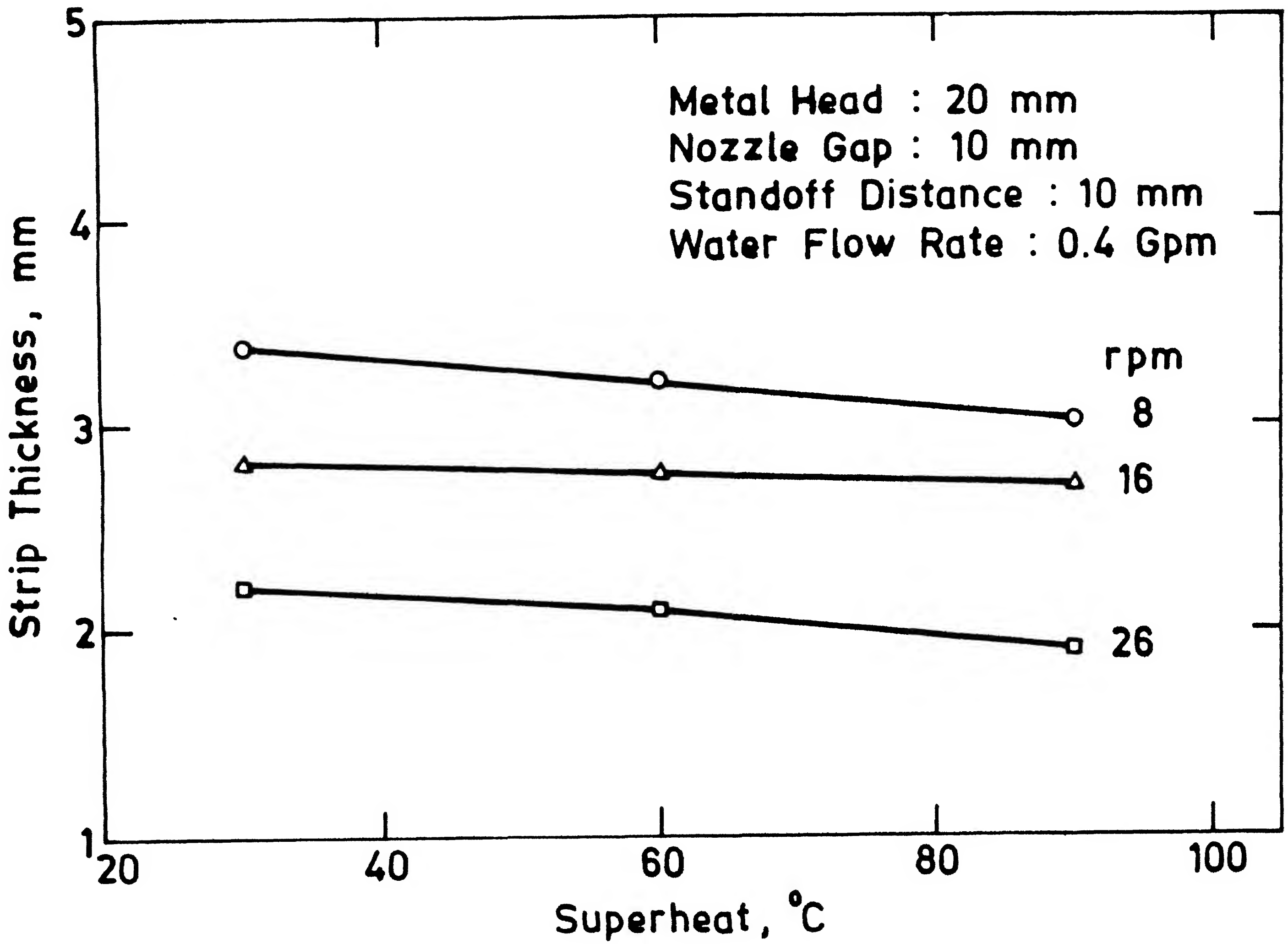



Fig. 5.2 Effect of Melt superheat on the Strip Thickness

namely 8, 16, and 26 rpm for a constant metal head of 20 mm, and the nozzle gap of 10 mm. It is to be noted that for constant rotational speed and other conditions remaining the same, the strip thickness decreases somewhat with increasing melt superheat. It is to be recognized that the temperature of the molten metal in the tundish is indicative of the total heat content of the melt. Larger amount of heat therefore must be removed through the solidifying strip in case of liquid metal with higher superheat. This, in turn, reduces the solidification rate. It is thus evident that the strip thickness reduces with increasing melt superheat. It may be pointed out that our experimental observation are in conformity with the theoretically predicted trends for steel by Mehrotra and coworkers.[19-24]

## 5.3 Effect of Liquid Metal Head in the Tundish

The effect of metal-head on the strip thickness is shown in Fig. 5.3 in which the strip thickness is plotted as a function of metal-head in the tundish for three different rpm values (8, 16, and 26 rpm) for a constant nozzle gap of 10 mm, melt superheat of 35°C and water flow rate of 0.4 gallons per minute. It is to be noted that the strip thickness is substantially increased (at all three rotational speeds) as the metal head is increased from 20 to 40 mm.

Molten metal head in the tundish determines the meniscus level of the molten metal in the metal pool. Thus, it determines the size of this pool. At a constant speed of rotation of the

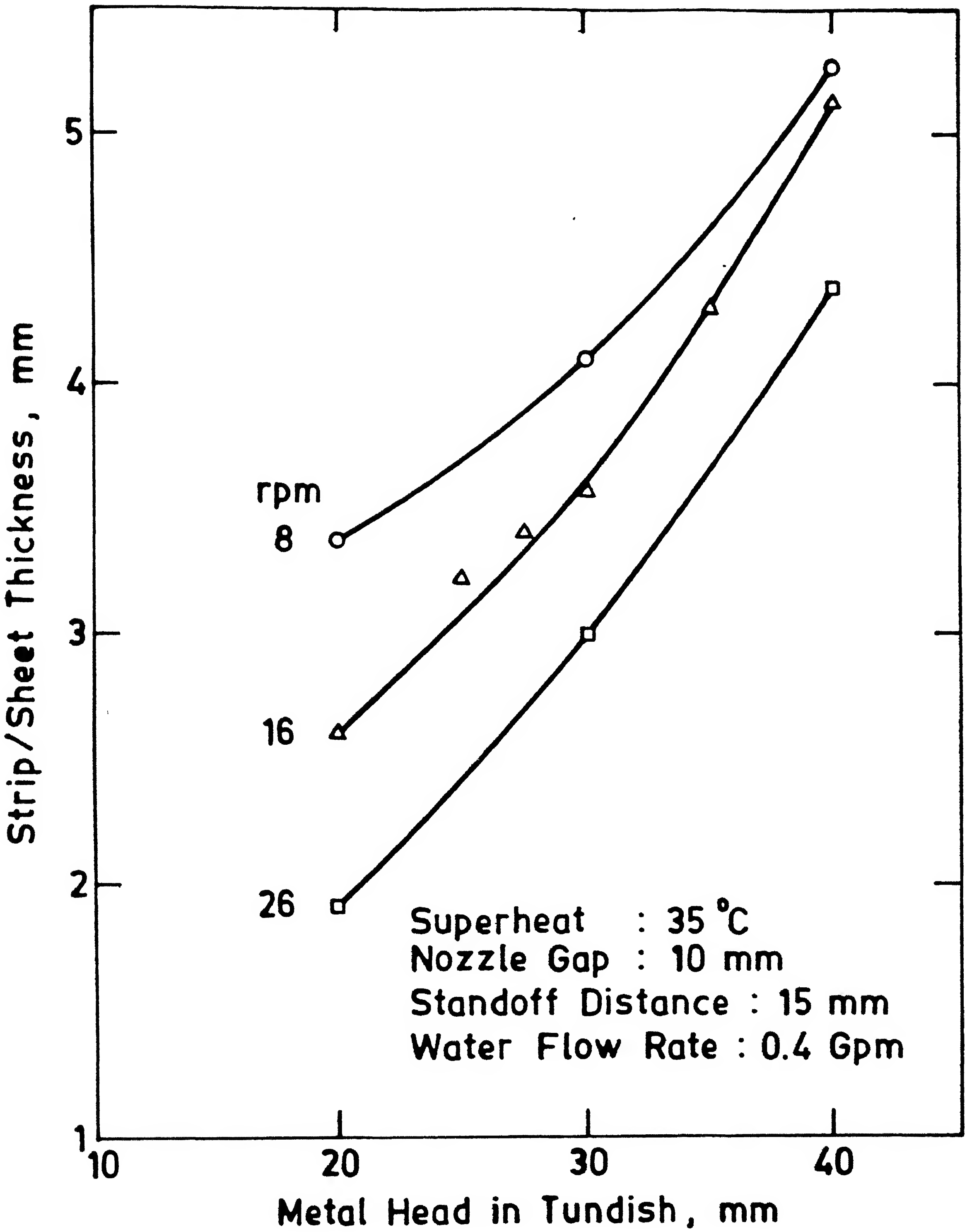



Fig. 5.3 Effect of Metal Head on the Strip Thickness

caster drum, the residence time of the solidifying strip in the metal pool directly depends on the pool size. Larger the pool size, larger will be the duration for which the solidifying strip is in contact with the molten metal. This, in turn, leads to thicker strips.

## 5.4 Effect of Nozzle gap on Strip Thickness

The effect of nozzle gap on strip thickness is shown in Fig. 5.4. In this figure the strip thickness is plotted as function of nozzle gap for three different values of rotational speeds namely 8, 16, and 26 rpm for constant values of metal-head of 20 mm, superheat 35°C, and water flow rate of 0.4 gallons per minute, respectively. It is to be noted that as the nozzle gap increases the strip thickness somewhat decreases.

This observation is not in conformity with the simulated results of Mehrotra and Tandon,[22] who, using a mathematical model based on fluid mechanics consideration only, predicted that the strip thickness would increase with increasing nozzle gap. It may, however, be pointed out that in their model the tundish is visualized to have a converging type of nozzle through which the metal is transferred from the tundish to the metal pool, whereas in the present investigation there is no such nozzle metal flows through a slid opening in the tundish. The effect of nozzle opening is likely to be more predominent in the case of a converging nozzle because the reduction in the nozzle gap will result in larger frictional 'Head Loss' which reduces the metal

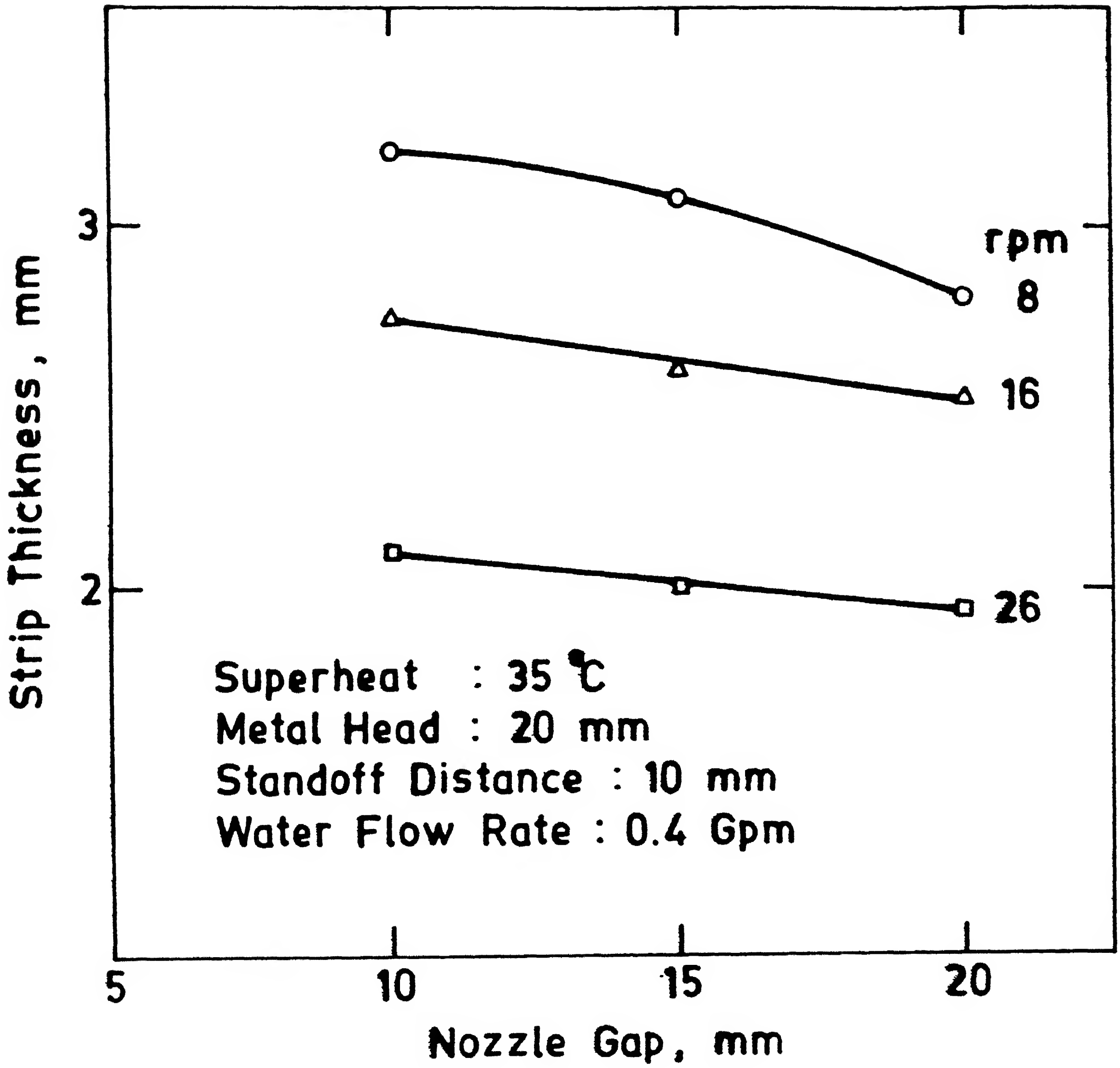



Fig. 5.4 Effect of Nozzle gap on the Strip Thickness

velocity at the exit point resulting in reduced metal flow rate. In case of a tundish with a slid opening only, the flow rate is going to be controlled primarily by the metal head in the tundish.

## 5.5 Effect of Standoff Distance ($\delta$)

The effect of standoff distance on strip thickness is shown in Fig. 5.5 in which the strip thickness is plotted as a function of standoff distance for three different rotational speeds. It may be seen that the final strip thickness increases with increasing standoff distance. These observations are in confirmity with those of Mehrotra and coworkers,[22-24] who predicted this behaviour using various mathematical models for this process. Pimputkar et al.[3] have also reported similar behaviour in their experimental investigations. As Mallik and Mehrotra have argued, the fluid flow pattern of liquid steel in pool is directly related to standoff distance ($\delta$). The wall effects become more predominant with decreasing $\delta$. Thus, as the standoff distance decreases the velocity gradient in the metal pool increases. This results in a higher convective heat transfer in the pool which, in turn, results in larger amount of heat to be transferred to the solidifying strip. Therefore, for a given set of condition, smaller value of $\delta$ leads to reduced strip thickness.

## 5.6 Effect of Cooling Conditions Prevailing at the Inner Surface of the Caster Drum

Effect of cooling water on the strip thickness is shown in Fig. 5.6 which shows plots of strip thickness versus water flow

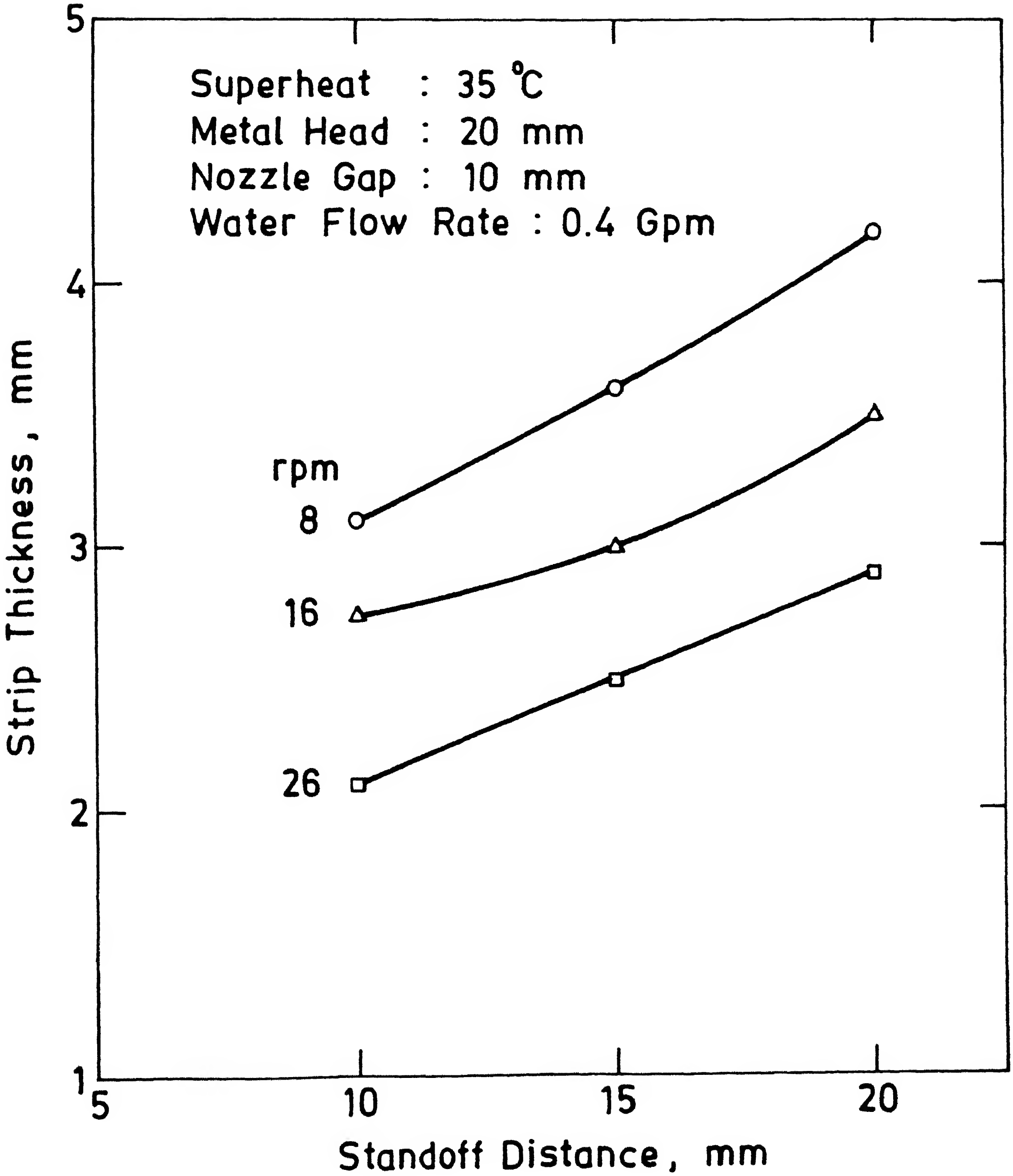



Fig. 5.5 Effect of Standoff Distance on the Strip Thickness

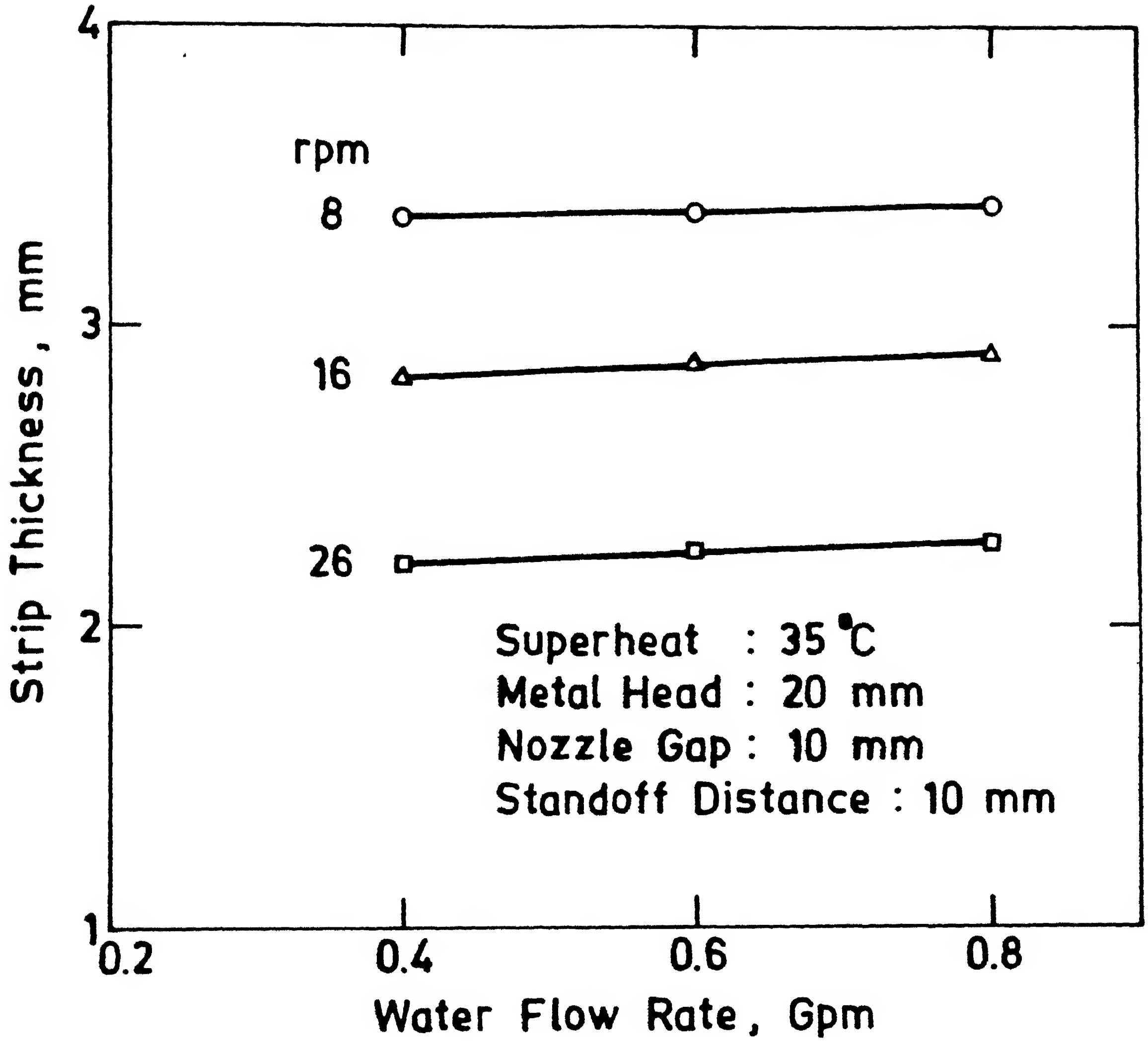



Fig. 5.6 Effect of Water Flow Rate on the Strip Thickness

rate at three different values of rotational speeds. It may be noted that the increase in water flow rate has only a very marginal effect on the strip thickness. Doubling the water flow rate from 0.4 gallons per minute to 0.8 gallons per minute increases the strip thickness by less than 5%. These findings are also in conformity with those of Mehrotra and coworkers.[19-24] As has been argued by them, the thermal conductivity of the solidifying steel strip is substantially lower than that of the copper caster drum. The cooling rate of the solidifying strip is primarily governed by the thermal gradient within this strip which is only very marginally affected by cooling conditions prevailing at the inner surface of the caster drum. It is, therefore, be concluded that the intensity of water spray inside the drum is not a critical parameter as far as controlling the strip thickness is concerned. Larger intensity of cooling at the inner drum surface only ensures that the temperature of the drum at no stage exceeds its softening temperature and thus no significant distortion of it takes place.

# CHAPTER 6

# SUMMARY AND CONCLUSION

The present investigation primarily involved the completion of design and fabrication of a Single Roll Strip caster, a task initiated by Mehrotra and coworkers. The main components of the caster are: tundish, caster drum, water sprays, kinfe edge, and a stepper motor. The tundish, which holds liquid metal, is made of refractory. Its wall facing the caster drum has a concentric profile with the latter. The tundish is positioned as close to the drum as possible without scratching its surface. A pool of molten metal is maintained in the annular space between the tundish and the caster drum.

The caster drum is a hollow cylinder made of copper. This drum can be rotated with the help of a stepper motor at a speed varying between 1.5 to 38 rpm. The speed of the stepper motor is controlled using a microprocessor based control system. The range of rotational speed can be further enlarged using a gear assembly.

Heat is extracted continuously from the internal surface of the caster drum by water spray which are located inside the drum. Cone type nozzles have specially been designed and fabricated for this purpose. The flow rate of input water is measured using a flow meter which is fixed on the water pipe-line. A knife edge located on the other side of the caster drum peels off the solidified strip from the caster drum and allows it to continuously flow on a slanted platform.

A provision is also made to continuously monitor the temperature of the caster drum wall at two locations during the casting operation. The temperatures are measured through chrommel-alumel thermocouples, the output of which is directly fed to a PC Based Data Acquisition System. The latter consists of a HCL Busy Bee PC with a PCL 212 card attached to it. The PCL 212 card has eight channels to continuously record temperatures at eight different locations. The data is stored in a floppy and can be displayed on the PC monitor as and when required.

Aluminium strips of about 2 m length, 0.1 m width and varying thicknesses have been produced under various operating conditions. In all, more than sixty experiments have been carried out by varying the following operating variables, one at a time:

(i) Rational speed of the caster drum

(ii) Metal head in the tundish

(iii) Superheat of molten metal

(iv) Standoff distance (distance between the caster drum surface and the concentric tundish wall)

(v) Nozzle gap

(vi) Water flow rate which determines the cooling conditions prevailing at the inner surface of the caster drum.

Effect of these variables on the strip thickness has been investigated. From the analysis of the experimental results following conclusions are drawn:

1) Rotational speed of the caster drum is perhaps the most

critical operating variable. Increased speed of rotation gives thinner strips. The effect of rotational speed is more predominant at lower speeds.

2) Strips thickness increases with increasing molten metal head in the tundish.

3) Increased superheat results in production of thinner strips.

4) Increased standoff distance results in thicker strips.

5) The effect of tundish nozzle opening size on the strip thickness is only marginal - strip thickness very slightly decreases with increasing nozzle gap. However, from the design point of view this may be an important parameter. Too small a nozzle gap may lead to more frequent nozzle clogging and thus disrupt the process.

6) Like the nozzle gap, the cooling conditions prevailing at the inner surface of the caster drum, have only a marginal effect on the strip thickness. It, however, has a significant effect on the temperature distribution within the caster drum. A minimum cooling rate is required to ensure that the caster drum temperature at no stage exceeds its softening temperature which would otherwise lead to distortion of the drum.

# REFERENCES


1. Mehrotra S.P., Koria S.C. (Eds.), 'Short Term Course on Continuous Casting of Steel', I.I.T. Kanpur, July 1989.
2. Mehrotra S.P., 'Continuous Casting of Thin Slabs/Strips of Steel', Indian Steel Annual, 1991, pp 97-101.
3. Pimputkar S.M., Carbonara R.S., Rayment J.J., McCall J.L., Clauer A.H., 'Comparison of the Single and Double Roller Caster Process for Casting Low Carbon Steel', Rapidly Quenched Metals; Steeb S., Warlimont (Eds.) Elsevir Pub., 1985, pp 95-100.
4. Reichelt W., Werner K., 'Near-Net-Shape Casting of Flat Products', Met. Plant and Technology, Vol. 11, 1988, pp 18-35.
5. Cramb A.W.,'New Steel Casting Processes for Thin Slabs and Strips- A Historical Perspective', Iron and Steelmaker, July 1988, pp 45-60.
6. Teoh L.L., 'Technological Developments in Continuous Thin Slab and Strip Casters', Iron and Steel Engineer, Dec. 1988, pp 34-40.
7. Anjan Kumar M.K., 'Mathematical Modelling of Continuous Casting of Steel Strips', M.Tech. thesis, Department of Met. Engg., I.I.T. Kanpur, May 1990.
8. Ratan Kumar Mallik, 'Fluid Flow and Heat Transfer Model of Continuous Casting of Steel Strips', M. Tech. thesis, Department of Met. Engg., I.I.T. Kanpur, March 1991.

9. Petry C.J., Platek S.W., 'Progress Report on the Use of the Hazelett Process for Aluminimum Alloy Strip-Casting', Light Metals, AIME, 1983, pp 931-950.

10. Varley P.C., 'Technology of Aluminium and its Alloys', pp 15-16.

11. 'Light Metals and Metal Industry', March 1965, pp 40-45.

12. Essadiqi E., Caron S., Hamel F.G. and Masounave J., 'Casting of Al-Si Alloy', Production and Electrolysis of Light Metals, 1989, pp 69-78.

13. Iricibar R., Jim I., 'Rolling Aspects of Twin Roll Casting', Light Metals, AIME, 1984, pp 1129-1145.

14. Clarence J.M., 'Continuous Casting-Hunter Technology', Light Metals, AIME, 1982, pp 837-873.

15. Westengen H., Nes K., 'Twin Roll Casting of Aluminium', Light Metals, AIME, 1984, pp 1111-1126.

16. Jim I., Morris L.R., and Hunt J.D., 'Centreline Segregation in Twin-Roll Cast Aluminium Alloy Slab', Journal of Metals, June 1982, pp 70-74.

17. Edmonds D.V., Hunt J.D., 'An Experimental Study of Twin Roll Casting', Extraction Refining and Fabrication of Light Metals, 1991, pp 257-270.

18. Chopra O., Niesson P., 'Solidification of Lead and Lead Alloys in Continuous Drum Sheet Casting', Z. Metallkde, Vol. 66, 1975, pp 10-16.

19. Anjan Kumar M.K. and Mehrotra S.P., 'A Mathematical Model of Single Roll Strip Caster Based on Macroscopic Enthalpy Balances', Steel Res., Vol. 62, No. 4, 1991, pp 161-170.

20. Anjan Kumar M.K. and Mehrotra S.P., 'Effect of Process Parameters on the Performance of a Single Roll Continuous Strip Caster', in Proc. of Ist European Conference on Continuous Casting, Publ. Associaziane Italiana Di Metallurgia, Vol. 2, 1991, pp. 367-376.

21. Anjan Kumar M.K. and Mehrotra S.P., 'Mathematical Model of Single Roll Strip Caster Based on Microscopic Heat Balance', Ironmaking and Steelmaking, Vol. 19, No. 1, 1992, pp 55-63.

22. Mehrotra S.P. and Tandon R., 'A Mathematical Model of a Single Roll Continuous Strip Caster Based on Fluid Mechanics Considerations', Steel Res., Vol. 63, 1992, pp 205-211.

23. Mallik R.K. and Mehrotra S.P., 'Mathematical Modelling of Single Roll Continuous Strip Caster Based on Fluid Flow and Heat Transfer Considerations',JSIJ International, Vol. 33, May 1993, (to be published).

24. Shamsi M.R.R.I and Mehrotra S.P, 'A Two Dimensional Heat and Fluid Flow Model of Single Roll Continuous Sheet Casting Process', Metallurgical Transaction B, Vol. 24B, June 1993, (to be published).

# Appendix I

## Microprocessor Programme to Run Stepper Motor

(Numbers written within Brackets control the Motor Speed)

| | |
|---|---|
| 1010 | 3E |
| 1011 | 80 |
| 1012 | D3 |
| 1013 | 03 |
| 1014 | 3E |
| 1015 | 05 |
| 1016 | D3 |
| 1017 | 00 |
| 1018 | CD |
| 1019 | 00 |
| 101A | 14 |
| 101B | 3E |
| 101C | 01 |
| 101D | D3 |
| 101E | 00 |
| 101F | CD |
| 1020 | 00 |
| 1021 | 14 |
| 1022 | 3E |
| 1023 | 09 |
| 1024 | D3 |
| 1025 | 00 |
| 1026 | CD |
| 1027 | 00 |
| 1028 | 14 |
| 1029 | 3E |
| 102A | 08 |
| 102B | D3 |
| 102C | 00 |
| 102D | CD |
| 102E | 00 |
| 102F | 14 |
| 1030 | 3E |
| 1031 | 0A |
| 1032 | D3 |
| 1033 | 00 |
| 1034 | CD |
| 1035 | 00 |
| 1036 | 14 |
| 1037 | 3E |
| 1038 | 02 |
| 1039 | D3 |
| 103A | 00 |
| 103B | CD |
| 103C | 00 |
| 103D | 14 |
| 103E | 3E |
| 103F | 06 |
| 1040 | D3 |
| 1041 | 00 |
| 1042 | CD |
| 1043 | 00 |
| 1044 | 14 |
| 1045 | 3E |
| 1046 | 04 |
| 1047 | D3 |
| 1048 | 00 |
| 1049 | CD |
| 104A | 00 |
| 104B | 14 |
| 104C | C3 |
| 104D | 14 |
| 104E | 10 |
| 104F | 76 |
| 1400 | 11 |
| 1401 | FF |
| 1402 | ( ) |
| 1403 | CD |
| 1404 | F1 |
| 1405 | 05 |
| 1406 | C9 |

| Machine Code | RPM of Drum |
|---|---|
| 01 | 38 |
| 02 | 26 |
| 03 | 20 |
| 04 | 16 |
| 05 | 14 |
| 06 | 12 |
| 07 | 10 |
| 08 | 08 |
| 10 | 4.5 |
| 12 | 3.5 |
| 25 | 1.5 |